

Szkoła Doktorska Nauk Przyrodniczych i Rolniczych w Krakowie

Instytut Ochrony Przyrody Polskiej Akademii Nauk



Mgr inż. Jolanta Pilch

Rekonstrukcja zmian paleośrodowiska polskich Karpat zachodnich w późnym glacjale, w oparciu o analizy litologiczne i makroszczątków roślin z osadów wybranych torfowisk osuwiskowych

Reconstruction of the Late Glacial paleoenvironmental changes of the Polish Western Carpathians, on the base of lithological and plant macrofossils analyses of the selected landslide fen deposits

Rozprawa doktorska

Doctoral Thesis

Promotorzy:

Dr hab. inż. Włodzimierz Margielewski, prof. IOP PAN

Dr hab. Renata Stachowicz-Rybka

Kraków, 2025

*Składam serdeczne podziękowania
dr hab. inż. Włodzimierzowi Margielewskiemu, prof. IOP PAN oraz
dr hab. Renacie Stachowicz-Rybce,
za nieocenioną pomoc i opiekę promotorską, okazane wsparcie,
życzliwość oraz poświęcony czas.*

*Dziękuję dr Krzysztofowi Buczkowi z IOP PAN
za pomoc i wsparcie, szczególnie terenowe i techniczne.*

*Dziękuję mgr inż. Andrzejowi Kalembie oraz wszystkim pracownikom IOP PAN oraz IB PAN
za okazaną pomoc i życzliwość podczas realizacji tematu pracy doktorskiej.*

*Dziękuję Kierownictwu i Radzie Szkoły Doktorskiej Nauk Przyrodniczych i Rolniczych w
Krakowie za możliwość realizacji niniejszego projektu badawczego.*

Spis treści

1. Lista publikacji wchodzących w skład rozprawy doktorskiej.....	6
2. Finansowanie.....	8
3. Streszczenie.....	9
4. Summary.....	11
5. Wprowadzenie.....	13
5.1. Specyfika torfowisk osuwiskowych jako czułych indykatorów zmian paleośrodowiska.....	13
5.2. Problematyka podziału chronostratygraficznego późnego glacjału.....	13
5.3. Zapis zmian paleoklimatycznych i paleośrodowiskowych w osadach a położenie topograficzne torfowisk Kotoń i Klaklowo.....	15
5.4. Zmiany w składzie makroszczątków roślin stwierdzone na podstawie kilku rdzeni osadów nawierconych w różnych strefach jednego torfowiska.....	16
5.5. Chłodna oscylacja klimatyczna starszego dryasu.....	17
5.6. Refugia roślin ciepłolubnych.....	18
5.7. Poziomy tefry w osadach.....	20
6. Cel pracy i hipotezy badawcze.....	21
7. Teren badań.....	22
7.1. Lokalizacja, geologia i geomorfologia.....	22
7.2. Klimat.....	23
7.3. Charakterystyka osuwisk.....	23
7.4. Zagłębienia pod skarpą główną, hydrologia i osady torfowiskowe.....	24
7.5. Gleba i roślinność.....	24
8. Metody badań.....	25
8.1. Pobór materiału do badań.....	25
8.2. Datowanie radiowęglowe i opracowanie modelu wiek-głębokość.....	25
8.3. Analiza strat prażenia oraz określenie typu torfu.....	26
8.4. Analiza makroszczątków roślin.....	27
8.5. Analiza palinologiczna i analiza palinomorf niepyłkowych (NPPs).....	28
8.5.1. Rdzenie główne.....	28
8.5.2. Rdzenie boczne.....	29
8.6. Analiza uziarnienia (granulometryczna).....	30
8.7. Analiza potencjalnych poziomów tefry związanych z erupcjami wulkanów w późnym glacjału.....	30
8.8. Dodatkowe analizy geochemiczne.....	31

8.9.	Analizy statystyczne	33
9.	Wyniki	34
9.1.	Wyniki dla głównego celu badawczego 1a – publikacja 1	34
9.2.	Wyniki dla głównego celu badawczego 1b – publikacje 1, 2 i 3 oraz materiały niepublikowane	35
9.3.	Wyniki dla głównego celu badawczego 1c – publikacje 2 i 3	37
9.3.1.	Rekonstrukcja etapów rozwoju torfowisk i korelacja z ponadregionalnymi chronologiami absolutnymi	37
9.3.2.	Charakterystyka szaty roślinnej	38
9.3.3.	Podobieństwa w zapisie zmian szaty roślinnej pomiędzy stanowiskami	39
9.3.4.	Porównanie z chronozonami wyznaczonymi we wcześniejszych badaniach ..	39
9.4.	Wyniki dla drugorzędnego celu badawczego 2a – publikacje 1, 2 i 3 oraz materiały niepublikowane	41
9.5.	Wyniki dla drugorzędnego celu badawczego 2b – materiały niepublikowane	44
10.	Wnioski i podsumowanie	45
11.	Literatura	47
12.	Figury	57
13.	Tabele	70
14.	Załączniki	80
14.1.	Publikacja 1 – Tytuł	80
14.2.	Publikacja 1 – Oświadczenia współautorów	81
14.3.	Publikacja 1	82
14.4.	Publikacja 2 – Tytuł	203
14.5.	Publikacja 2 – Oświadczenia współautorów	204
14.6.	Publikacja 2	213
14.7.	Publikacja 3 – Tytuł	264
14.8.	Publikacja 3 – Oświadczenia współautorów	265
14.9.	Publikacja 3	270

1. Lista publikacji wchodzących w skład rozprawy doktorskiej

Rozprawa składa się z trzech artykułów naukowych, których pierwszym i korespondencyjnym autorem jest doktorantka, oraz z materiałów niepublikowanych. Wszystkie artykuły zostały złożone w międzynarodowych czasopismach z listy Journal Citation Reports, posiadających Impact Factor (IF). Dwa z nich zostały opublikowane (publikacja 2 i 3), zaś jeden znajduje się na etapie recenzji (publikacja 1).

Publikacja 1

Pilch, J., Margielewski, W., Stachowicz-Rybka, R., Buczek, K., Obidowicz, A., Korzeń, K., 202x. Effect of topographic position on differential biotic and lithological responses to the late glacial–early Holocene climatic oscillations recorded in sediments of two landslide fens (the Outer Western Carpathians, S Poland). (Artykuł na etapie recenzji w czasopiśmie *The Holocene*).

MNISW (2024 rok): 140 pkt.

IF: (5-letni) 2,2; (2024 rok) 1,8

Publikacja 2

Pilch, J., Margielewski, W., Stachowicz-Rybka, R., Buczek, K., Stolarczyk, M., Musielok, Ł., Korzeń, K., Sala, D., 2025. Characeae-dominated vegetation succession as a key to understanding the late glacial environmental changes (ca. 14,600–13,500 cal yrs BP): a multi-proxy record of palaeo-waterbody developed within the Klaklowo landslide, the Outer Western Carpathians, S Poland. *Journal of Paleolimnology* 73, 195–215. <https://doi.org/10.1007/s10933-025-00355-1>

MNISW (2024 rok): 100 pkt.

IF: (5-letni) 1,7; (2024 rok) 1,3

Publikacja 3

Pilch, J., Margielewski, W., Stachowicz-Rybka, R., Buczek, K., 2025. The Bølling-Older Dryas-Allerød transition (ca. 14,600–13,500 cal BP) in the palaeoecological record of the Kotoń landslide fen (the Outer Western Carpathians, S Poland) – from the local to extraregional

perspective. Radiocarbon 1–21. <https://doi.org/10.1017/RDC.2025.10122>

MNISW (2024 rok): 140 pkt.

IF: (5-letni) 4,9; (2024 rok) 1,3

Sumaryczna punktacja MNISW: 380 pkt.

Sumaryczny IF: (5-letni) 8,8; (2024 rok) 4,4

2. Finansowanie

Badania wchodzące w skład rozprawy doktorskiej finansowane były następująco:

- 1) Dr hab. inż. Włodzimierz Margielewski z Instytutu Ochrony Przyrody PAN, który jest jednym z promotorów rozprawy doktorskiej, uzyskał środki finansowe w ramach finansowania projektu badawczego z Narodowego Centrum Nauki, o numerze rejestracyjnym 2020/39/O/ST10/03504 (2021-2025) PRELUDIUM BIS 2 i o tytule: „Rekonstrukcja zmian paleośrodowiska polskich Karpat zachodnich w późnym glacie, w oparciu o analizy litologiczne i makroszcątków osadów wybranych torfowisk osuwiskowych”, którego został Kierownikiem, zaś mgr inż. Jolanta Pilch korzystała z tych środków na realizację projektu jako Doktorantka-Stypendystka.



PRELUDIUM BIS-2

- 2) Doktorantka uzyskała środki finansowe z Narodowej Agencji Wymiany Akademickiej w ramach realizacji zagranicznego stażu doktorskiego NAWA PRELUDIUM BIS 2 (BPN/PRE/2022/1/00033/U/00001).



- 3) Doktorantka uzyskała dotację dla młodych naukowców w ramach konkursu i finansowania wewnętrznego Instytut Ochrony Przyrody PAN uzyskanej dla projektu o tytule: „Dynamika rozwoju łąk ramienicowych w strefie przybrzeżnej podczas ocieplenia klimatu alleroð w zapisie kopalnym torfowisk osuwiskowych Klaklowo i Kotoń (ok. 13 620–13 870 lat cal BP) oraz implikacje dla współczesnych zbiorników wodnych w kontekście zmian klimatu”.



3. Streszczenie

Torfowiska osuwiskowe to rodzaj minerogenicznych torfowisk górskich, które rozwijają się w zagłębieniach osuwiskowych. W porównaniu do torfowisk zlokalizowanych na obszarach nizinnych, charakteryzują się one większą dynamiką reżimu hydrologicznego oraz częstszą dostawą materiału minerogenicznego do basenu sedymentacyjnego. Dzięki takim uwarunkowaniom, w osadach torfowisk, jak również jezior osuwiskowych, w sposób bardzo szczegółowy zostały zarejestrowane zmiany paleoklimatu i paleośrodowiska późnego glacjału i holocenu. Dwa torfowiska osuwiskowe, Kotoń i Klaklowo w Beskidzie Makowskim (Karpaty zachodnie), są szczególnie interesujące właśnie ze względu na unikatowe sekwencje rzadko udokumentowanych osadów późnoglacialnych i holocenijskich o dużych miąższościach. Celem badań osadów tych torfowisk osuwiskowych było: i) porównanie zapisu późnoglacialnych i holocenijskich zmian klimatycznych z uwzględnieniem wpływu zróżnicowanego usytuowania topograficznego tych stanowisk, ii) określenie zmian w składzie makroszczałków roślin w obrębie dwóch profili, pobranych z różnych stref tego samego torfowiska, iii) określenie lokalnych i regionalnych zmian roślinności w starszym dryasie. Dodatkowo, celem pracy doktorskiej było: iv) zweryfikowanie występowania w późnym glacialu refugium roślin termofilnych na obszarze osuwiska Kotoń oraz v) identyfikacja poziomów tefry (pyłu wulkanicznego), związanych z erupcjami wulkanów w późnym glacialu na terenie Europy.

Rdzenie główne osadów torfowiskowych pobrano w miejscach o największej miąższości osadów, 500 i 367 cm, odpowiednio dla torfowiska Kotoń i Klaklowo. Pobrano również po dwa rdzenie boczne ze stref marginalnych zagłębień osuwiskowych (rdzeń boczny Klaklowo B1 i B2 oraz rdzeń boczny Kotoń B1 i B2). Rdzenie osadów następnie opróbowano i pozyskany materiał poddano analizie makroszczałków roślin, analizie pyłkowej, datowaniu radiowęglowemu, analizie strat prażenia, uziarnienia i geochemicznej.

W badaniach wykazano, że (z pewnymi odstępstwami) ekspansja i/lub zanik dominujących taksonów roślin (*Pinus*, *Betula* sect. *Albae*, *Carex*, Bryopsida) oraz zmiany w dostawie materii minerogenicznej spowodowane globalnymi zmianami klimatycznymi (wg chronologii absolutnej rdzeni Grenlandii): ociepleniem alleroðu (GI-1a-c, 13 904–12 846 lat BP), ochłodzeniem młodszego dryasu (GS-1, 12 846–11 653 lat BP) i ociepleniem holocenijskim (<11 653 lat BP), następowały w przybliżeniu w tym samym czasie na torfowiskach osuwiskowych Klaklowo i Kotoń i nie były uwarunkowane ekspozycją i/lub wysokością położenia torfowisk. Z drugiej strony, w czasie trwania krótszych oscylacji klimatycznych, ochłodzenia Gerzensee (GI-1b, 13 261–13 049 lat BP) i chłodnej oscylacji preborealnej (ok. 11 400–11 100 lat cal BP), zaobserwowano znacznie wyraźniejszy zapis litologiczny

(wzmoczona dostawa materiału minerogenicznego) w obrębie torfowiska Klaklowo, niż w przypadku sekwencji osadowej stanowiska Kotoń, co mogło wynikać z charakterystyki zlewni torfowiska Klaklowo, w tym jej powierzchni, kształtu, morfologii stoku, geologii podłoża skalnego i specyficznych lokalnych form rzeźby terenu.

W przypadku obydwu stanowisk, stwierdzono, iż profile główne osadów pobrane w centralnej części torfowisk są nie tylko reprezentatywne dla całego zbiornika sedymentacyjnego, ale też pozwalają (w związku z większą miąższością osadów) odtworzyć więcej etapów rozwoju torfowiska o wyraźniej sprecyzowanych granicach w stosunku do rdzeni bocznych Klaklowo B1 i Kotoń B1 nawierconych w strefach marginalnych torfowisk.

Oscylacja klimatyczna starszego dryasu (GI-1d, 14 025–13 904 lat BP), związana z oddziaływaniem zimnego i suchego klimatu kontynentalnego, w sekwencjach osadowych zarówno Kotonia jak i Klaklowa reprezentowana jest przez zespoły makroszczątków roślin, wskazujące na występowanie stepo-tundry i panowanie arktyczno/alpejskich warunków klimatycznych. W przypadku lokalnych zmian roślinności i paleohydrologicznych, oscylacja klimatyczna GI-1d/starszego dryasu została zarejestrowana podobnie w obydwu stanowiskach, jako wypłylenie istniejących paleo-zbiorników wodnych.

W oparciu o wyniki analiz palinologicznych wykonanych dla profili głównych i bocznych wykazano, iż pyłek roślin termofilnych (*Corylus*, *Ulmus*, *Quercus*, *Tilia*, *Carpinus betulus*) w późnoglacialnych sekwencjach osadów torfowisk Kotoń i Klaklowo jest redeponowany ze starszych pokryw stokowych. Również w zapisie makroszczątków roślin nie stwierdzono obecności nasion, owoców lub części wegetatywnych roślin, wskazujących na lokalne występowanie tych taksonów. Hipoteza o występowaniu refugium roślin ciepłolubnych na stanowisku Kotoń w późnym glacie nie została zatem potwierdzona bieżącymi wynikami badań.

W przedziałach głębokości wytypowanych (na podstawie wieku modelowanego) do analizy potencjalnych horyzontów tefry Neapolitan Yellow Tuff (NYT) oraz Laacher See Tephra (LST), zarówno w przypadku stanowiska Klaklowo jak i Kotoń stwierdzono występowanie licznych ziaren posiadających cechy tefry, jednakże konieczne jest przeprowadzenie szczegółowych analiz geochemicznych, aby potwierdzić ich pochodzenie z poszczególnych erupcji: NYT i LST.

Wyniki przeprowadzonych badań stanowią znaczący wkład w stan wiedzy o lokalnych i regionalnych zmianach szaty roślinnej, chronostratygrafii i klimatostratygrafii późnego glaciału oraz dają solidne podstawy do dalszych bardziej szczegółowych badań typu multi-proxy osadów torfowisk osuwiskowych w Karpatach zachodnich.

4. Summary

Landslide fens are a type of mountain minerogenic mires that develop in landslide depressions. Comparing to the typical lowland mires they are characterized by a more variable hydrological regime and a greater dynamics of minerogenic material delivery to the sedimentary basin. Owing to such conditions, in the sediments of landslide mires, as well as landslide lakes, changes in the late glacial and Holocene palaeoclimate and palaeoenvironment could be recorded in a great detail. Two landslide fens, Kotoń and Klaklowo in the Beskid Makowski Mountains (the Western Carpathians), are particularly interesting due to the unique sequences of rarely documented late glacial and Holocene sediments of great thicknesses. The aim of the study of sediments from these landslide fens was to: i) compare the record of late glacial and Holocene climate changes, taking into account the influence of the different topographical position of these sites, ii) determine changes in the composition of plant macrofossils within two profiles collected from different zones of the same landslide fen, iii) determine local and regional vegetation changes during the Older Dryas climatic oscillation. Additionally, the aim of the doctoral thesis was to: iv) verify the occurrence of thermophilous plant refugia in the Kotoń landslide area during the late glacial, and v) identify tephra (volcanic ash) levels associated with volcanic eruptions during the late glacial.

Main cores of fen sediments were collected from the spots characterised by deposits of the greatest thicknesses, 500 and 367 cm for the Kotoń and Klaklowo sites, respectively. Two lateral cores were also collected from each of the landslide depression marginal zones (lateral cores Klaklowo B1 and B2, lateral cores Kotoń B1 and Kotoń B2). The sediment cores were then sampled and the obtained material was subjected to plant macrofossil analysis, pollen analysis, radiocarbon dating, loss on ignition, grain size and geochemical analysis.

The study showed that (with some exceptions) the expansion and/or disappearance of dominant plant taxa (*Pinus*, *Betula* sect. *Albae*, *Carex*, Bryopsida) and changes in the supply of minerogenic matter caused by global climate shifts (according to Greenland ice cores absolute chronology): Allerød warming (GI-1a–c, 13,904–12,846 years BP), Younger Dryas cooling (GS-1, 12,846–11,653 years BP) and Holocene warming (<11,653 years BP), occurred at approximately the same time in the Klaklowo and Kotoń landslide fens and were not conditioned by the exposure and/or altitude of the sites. On the other hand, during shorter climatic oscillations, Gerzensee colling (GI-1b, 13,261–13,049 years BP) and the cold Preboreal oscillation (ca. 11,400–11,100 years BP), a much more pronounced lithological record (increased supply of minerogenic material) was observed within the Krakow fen than in the sedimentary sequence of the Kotoń site, which could be conditioned by the characteristics

of the Klaklowo fen catchment, including its area, shape, slope morphology, bedrock geology and specific local landforms.

In the case of both sites, it was found that the main sediment profiles collected in the central part of the fens are not only representative of the entire sedimentary basin, but also allow for the reconstruction of more stages of peatland development with more clearly defined stage boundaries than for the Klaklowo B1 and Kotoń B1 cores drilled in the marginal zones of the fens.

The Older Dryas climatic oscillation (GI-1d, 14,025–13,904 years BP), associated with the influence of a cold and dry continental climate, is represented in the sedimentary sequences of both Kotoń and Klaklowo fens by plant macrofossil assemblages which indicate the occurrence of steppe-tundra and prevalence of Arctic/alpine climatic conditions at that time. In the case of local vegetation and palaeohydrological changes, the GI-1d/Older Dryas climatic oscillation was recorded similarly at both sites, as a shallowing of existing palaeo-waterbodies.

Based on the results of pollen analyses conducted for the main and marginal cores, it was demonstrated that pollen of thermophilous plants (*Corylus*, *Ulmus*, *Quercus*, *Tilia*, *Carpinus betulus*) in the late glacial sediments of the Kotoń and Klaklowo fens is redeposited from the older slope covers. The plant macrofossil records also did not contain seeds, fruits, or vegetative parts of plants, indicating the local occurrence of these taxa. Therefore, the hypothesis of the occurrence of thermophilous plants refugia at the Kotoń site in the late glacial has not been confirmed by the current research results.

In the depth ranges selected (based on the modeled age) for the analysis of potential tephra horizons, the Neapolitan Yellow Tuff (NYT) and Laacher See Tephra (LST), both in the Klaklowo and Kotoń sites, numerous grains with tephra characteristics were found, however, detailed geochemical analyses are necessary to confirm their origin from the particular eruptions: NYT and LST.

The results of the conducted research make a significant contribution to the state of knowledge about local and regional changes in vegetation cover, chronostratigraphy and climatostratigraphy of the late glacial and provide a solid basis for further extended multi-proxy studies of the sediments of landslide fens in the Western Carpathians.

5. Wprowadzenie

5.1. Specyfika torfowisk osuwiskowych jako czułych indykatorów zmian paleośrodowiska

Torfowiska osuwiskowe to rodzaj minerogenicznych torfowisk górskich, które rozwijają się w zagłębieniach osuwiskowych i charakteryzują się bardzo zmiennym reżimem hydrologicznym oraz większą dynamiką dostawy osadu minerogenicznego do zbiorników sedymentacyjnych niż typowe torfowiska nizinne (Margielewski, 2014, 2018). Charakteryzuje je także duża zmienność zasilania wodą: od zasilania soligenicznego (oprócz wód podziemnych, jest to także woda spływająca po stoku), po ombrogeniczne. Na zmienność tego zasilania wskazują m.in. warstwy torfu ombrogenicznego, przeławicające torfy typowo minerogeniczne (turzycowe, drzewne, etc.) (Margielewski, 2006). Osady akumulowane w torfowiskach i jeziorkach osuwiskowych w sposób bardzo szczegółowy rejestrują zmiany paleośrodowiska późnego glacjału i holocenu, w tym wpływ regionalnych czynników klimatycznych, wpływ lokalnych uwarunkowań środowiska sedymentacyjnego (np. warunków hydrologicznych, dostępności materiału minerogenicznego, topografii basenu sedymentacyjnego torfowiska) oraz działalność człowieka, już od czasów prehistorycznych. Torfowiska osuwiskowe łączą cechy zarówno facji jeziorno-torfowiskowej, jak i stokowej (Margielewski, 2014, 2018). Torfowiska osuwiskowe są formami występującymi na obszarze Beskidu Makowskiego w zewnętrznych Karpatach zachodnich, gdzie stanowią unikatowe stanowiska zawierające w swoich sekwencjach osadowych obok osadów holocenijskich, rzadko występujące osady późnoglacialne o znacznych miąższościach (Margielewski i in., 2022b). Szczególnie interesujące są dwa torfowiska osuwiskowe, Kotoń i Klakłowo, posiadające osady organiczno-minerogeniczne o miąższościach odpowiednio 500 i 367 cm (Margielewski, 2001a, 2001b; Margielewski i in., 2003). Ze względu na zróżnicowane położenie topograficzne w obrębie tego samego masywu górskiego w Beskidzie Makowskim, stanowią one doskonałą okazję do korelacji profili i śledzenia wpływu regionalnych i lokalnych czynników środowiskowych (w tym wysokości, ekspozycji i cech zlewni) na zapis litologiczny i biotyczny w osadach jeziorno-torfowiskowych.

5.2. Problematyka podziału chronostratygraficznego późnego glacjału

W tradycyjnym podziale późnego glaciału, ocieplenia klimatu bølling i allerød rozdzielone są krótkim ochłodzeniem klimatu starszego dryasu, po allerødzie zaś następuje kolejne ochłodzenie: młodszego dryasu – takie następstwo sekwencji osadowych zostało ustalone na podstawie zapisu biostratygraficznego regionu Skandynawii (Iversen, 1954). Później fazy te przyjęto również jako formalne chronozony dla tej części Europy, przypisując chronozonie bølling (w połączeniu z występującym przed nią ochłodzeniem najstarszego dryasu) granice czasowe od 13,0 do 12,0 tys. lat uncal BP, chronozonie starszego dryasu od 12,0 do 11,8 tys. lat uncal BP, chronozonie allerød od 11,8 do 11,0 tys. lat uncal BP, a chronozonie młodszego dryasu od 11,0 do 10,0 tys. lat uncal BP (Mangerud i in., 1974). Klasyczny podział stratygraficzny późnego glaciału w różnych regionach Europy wydaje się być jednak bardzo zróżnicowany i problematyczny (De Klerk, 2004; Van Raden i in., 2013).

Dla regionu północnego Atlantyku, rdzenie lodowe GRIP z Grenlandii (stratygrafia zdarzeń/event stratygraphy INTIMATE oparta na zapisie izotopów tlenu) zostały zaproponowane jako stratotyp późnego glaciału o zakresie czasowym 22,0–11,5 tys. lat GRIP temu, z zaleceniem zastąpienia klasycznej terminologii: „bølling”, „starszy dryas”, „allerød” i „młodszy dryas” nowym schematem (Björck i in., 1998). W tym schemacie interfaza bølling-allerød miała w przybliżeniu odpowiadać interstadiałowi grenlandzkiemu 1 (GI-1), datowanemu na 14,7–12,65 tys. lat temu, podzielonemu na trzy cieplejsze epizody: GI-1a, 1c i 1e, rozdzielone chłodniejszymi oscylacjami: GI-1b i 1d. Z kolei młodszy dryas był identyfikowany ze stadią GS-1. Z drugiej jednak strony podkreślano, że chronologia rdzeni lodowych z Grenlandii nie powinna zastępować regionalnych podziałów stratygraficznych funkcjonujących na kontynencie, lecz być wykorzystywana bardziej jako ponadregionalny „reper” (Litt i in., 2001; Lowe i in., 2008; Van Raden i in., 2013). Badania, w których podejmowane są próby takich ponadregionalnych korelacji są liczne (Ammann i in., 2013; Bos i in., 2013; Dzieduszyńska i Forsytek, 2019; Feurdean i Bennike, 2004; Kołaczek i in., 2015; Litt i in., 2001; Margielewski i in., 2022a; Moska i in., 2022), niemniej jednak, należy brać pod uwagę ryzyko przeprowadzenia potencjalnie błędnej korelacji pomiędzy lokalnymi/regionalnymi wydzieleniami, a chronologią rdzeni lodowych Grenlandii, szczególnie w przypadku krótkotrwałych oscylacji klimatycznych (Rasmussen i in., 2014).

Warunkiem poprawnej korelacji między lokalnymi/regionalnymi wydzieleniami stratygraficznymi a stratygrafią rdzeni lodowych Grenlandii jest niezależna chronologia absolutna, oparta na danych radiowęglowych (Lowe i in., 2008), a także na innych metodach datowania, np. chronologii warwowej (Litt i in., 2001). W przypadku wcześniejszych badań

torfowisk osuwiskowych Kotoń i Klakłowo (Margielewski, 2001a, 2001b; Margielewski i in., 2003), brak było ciągłej chronologii absolutnej (modelu wiek-głębokość) opartej na datowaniach radiowęglowych AMS, co nie pozwoliło na przypisanie granicom chronozon (wyinterpretowanym w oparciu o dane palinologiczne) precyzyjnego, skalibrowanego wieku radiowęglowego. Co więcej, wcześniejsze badania obu stanowisk koncentrowały się bardziej na sekwencji holocenu, pozostawiając sekwencję osadów późnego glacjału jako zbadaną w niskiej rozdzielczości próbek i bez szczegółowej interpretacji. Brak zdefiniowanych ram czasowych dla rozpoznanych w przeszłości sekwencji chronostratygraficznych ustalonych na podstawie palinologii, jest częsty w Karpatach i na ich przedpolu (Harmata, 1987; Koperowa, 1961; Mamakowa, 1962; Ralska-Jasiewiczowa, 1980), jednakże w ostatnich czasach stwierdzono konieczność przypisania do późnoglacialnych/holocenijskich zapisów pyłkowych w tym regionie precyzyjnych i ciągłych chronologii absolutnych (Margielewski i in., 2022a; Micheczyński i in., 2013).

5.3. Zapis zmian paleoklimatycznych i paleośrodowiskowych w osadach a położenie topograficzne torfowisk Kotoń i Klakłowo

Wpływy lokalnego środowiska geomorfologicznego na późnoglacialne i wczesnoholocenijskie sekwencje osadowe jezior górskich i torfowisk (w tym torfowisk osuwiskowych) w Karpatach zachodnich były szczegółowo analizowane w skali pojedynczych stanowisk (Margielewski i in., 2010; Pánek i in., 2010; Šímová i in., 2019), a także przeanalizowane w ramach kompleksowych podsumowań regionalnych (Kłapyta i in., 2016; Margielewski, 2006, 2014, 2018). Chociaż regionalne korelacje osadów jezior i torfowisk górskich (również transekty przez takie stanowiska) dotyczą głównie zarejestrowanych w ich obrębie zmian biotycznych i klimatycznych, np. migracji granicy lasu, refugialnej roli lokalnych siedlisk czy wieku deglacjacji, często bada się również wpływ wysokości i ekspozycji na te zjawiska. Badania tego typu były przeprowadzone dla Tatr (Kłapyta i in., 2016), Karpat Rumuńskich i regionów przyległych (Feurdean i in., 2007, 2016; Magyari, 2002) lub dla Alp i regionów przyległych (Ammann i in., 2000; David, 1993; Lotter i in., 1992). Lokalne porównania osadów jeziornych/torfowiskowych pomiędzy blisko położonymi stanowiskami na obszarach górskich są rzadsze (Feurdean i Bennike, 2004) i czasami, pomimo niewielkiej odległości, zbliżonej wysokości i ekspozycji, zapis historii roślinności w obrębie

ich osadów jest wyraźnie zróżnicowany (Margielewski, 2006; Michczyński i in., 2013). Mniej powszechne są także korelacje pomiędzy stanowiskami położonymi w obrębie jednego masywu górskiego, ale o innej ekspozycji i wysokości (Magyari i in., 2018) i/lub o różnych cechach zlewni (Hubay i in., 2018; Rubensdotter i Rosqvist, 2003).

5.4. Zmiany w składzie makroszczątków roślin stwierdzone na podstawie kilku rdzeni osadów nawierconych w różnych strefach jednego torfowiska

Analizy palinologiczna, makroszczątków roślin oraz litologiczna przeprowadzone dla kilku rdzeni osadów jeziornych lub torfowiskowych pobranych z jednego stanowiska pozwala na rekonstrukcję zmian szaty roślinnej, sedymentacji osadów jeziornych, sedentacji osadów organicznych i wahań poziomu wody w różnych strefach zbiornika sedymentacyjnego (Kowalewski, 2014; Latałowa i Nalepka, 1987; Ralska-Jasiewiczowa i in., 1998). Jednakże, z uwagi na zróżnicowany potencjał tafonomiczny i reprezentatywność makroszczątków w osadzie względem przestrzennego rozmieszczenia macierzystych zbiorowisk roślinności w obrębie jeziora/torfowiska jak i w jego otoczeniu (Szymczyk, 2012), powstaje pytanie czy nawet w przypadku niewielkich zbiorników sedymentacyjnych analiza tylko jednego rdzenia osadów pozwala na kompletną rekonstrukcję etapów lokalnego rozwoju paleoekologicznego w skali czasu.

Przykładowo, rezultaty analizy makroszczątków o bardzo wysokiej rozdzielczości (1 cm) przeprowadzonej dla rdzeni pobranych w centralnej i marginalnej części niewielkiego górskiego torfowiska (i paleo-jeziora) Poiana Știol w Karpatach Wschodnich pozwoliły na bardzo szczegółową rekonstrukcję zmian szaty roślinnej na tym stanowisku w czasie trwania holocenu (Gałka i in., 2017). W badaniach tych, w celu ilościowego określenia kierunku i wielkości zmian w składzie gatunkowym lokalnej roślinności zarówno dla profilu osadów z centralnych partii zbiornika sedymentacyjnego, jak i w jego strefie marginalnej, zastosowano analizę PCA (Principal Component Analysis). Wyniki wykazały generalne następstwo fazy jeziornej i torfowiskowej obejmujące cały zbiornik, jednakże sukcesja roślinności w jego centralnej i marginalnej części przebiegała w odmienny sposób (Gałka i in., 2017).

Z kolei, podczas badań niewielkich i płytkich jezior w Norwegii, próbki osadów dennych zostały pobrane z najgłębszych partii jezior oraz wzdłuż transektów biegnących od ich centralnych części do strefy marginalnej (Heggen i in., 2012). Reprezentatywność każdej

próbki na tle zespołu wszystkich taksonów makroszczątków oznaczonych dla całego jeziora (tj. taksonów oznaczonych we wszystkie próbkach łącznie) określono poprzez porównanie wyników analizy PCA (PCA scores) oryginalnych danych z zestawem danych uzyskanych na drodze symulacji Monte Carlo (stosując bieżące dane jako ograniczniki symulacji). Wyniki pokazały, iż rdzenie osadów nawiercone w centralnych partiach jezior wykazują, w przeciwieństwie do rdzeni nawierconych w strefach marginalnych, najwyższe prawdopodobieństwo reprezentowania całego zespołu makroszczątków określonych dla osadów danego jeziora, jednakże te drugie posiadają najwyższy udział makroszczątków roślin lądowych (Heggen i in., 2012).

Różnice w zapisie palinologicznym i litologicznym pomiędzy profilami osadów nawierconych w różnych strefach torfowisk osuwiskowych Klakłowo i Kotoń zostały udokumentowane we wcześniejszych badaniach tych stanowisk (Margielewski i in., 2022b), jednakże porównanie takie nie zostało dotychczas wykonane dla analizy makroszczątków roślin.

5.5. Chłodna oscylacja klimatyczna starszego dryasu

Dotychczasowe badania paleośrodowiskowe osadów torfowisk osuwiskowych Klakłowo i Kotoń, wskazały na występowanie wyjątkowo mięjszych, ok. 0,5 m, sekwencji osadów minerogeniczno-organicznych przypisywanych krótkotrwałej (100–200 lat) chronozonie starszego dryasu (Margielewski, 2001b, 2001a; Margielewski i in., 2022b, 2003).

Sekwencje osadowe z zapisem oscylacji klimatycznej starszego dryasu, wydzielonej na podstawie danych pyłkowych jako tradycyjna zona biostratygraficzna lub chronozona (Iversen, 1954; Mangerud i in., 1974), są liczniejsze niż te, w których starszy dryas jest skorelowany z epizodem ochłodzenia GI-1d (14 025–13 904 lat BP), zdefiniowanym na podstawie chronologii absolutnej rdzeni lodowych Grenlandii (Rasmussen i in., 2014). Na nizinnych obszarach Europy, dawnym przedpolu ustępującego lądolodu zlodowacenia vistuliańskiego, osady starszego dryasu są często rejestrowane w stanowiskach związanych z późnoglacialną aktywnością eoliczną, np. w obrębie wydm, pokryw piaszczystych i na obszarach lessowych (Wasylikowa, 1964). Rejestrowano je także w sekwencjach osadowych jezior na obszarach równin europejskich (Nalepka, 2005; Novik i in., 2010; Ralska-Jasiewiczowa i in., 1998; Zernitskaya, 1997) czy w osadach torfowiskowych (Latałowa i Nalepka, 1987; Nalepka, 1994).

Starszy dryas został stwierdzony w kotlinach śródgórskich Karpat zewnętrznych (Harmata, 1987) i wewnętrznych (Koperowa, 1961; Margielewski i in., 2022a), a także w Tatrach (Baumgart-Kotarba i Kotarba, 1993; Obidowicz, 1993, 1996). Z drugiej strony, ochłodzenie klimatu w trakcie trwania starszego dryasu bardzo słabo (niekiedy w ogóle) nie zaznaczyło się w osadach późnoglacialnych stanowisk z Wysp Brytyjskich, dlatego fazy *bølling* i *allerød* są tam uważane za jeden interstadium, podczas gdy wydzielenie starszego dryasu jest kwestionowane (Watts, 1980). Podobny problem z wyodrębnieniem starszego dryasu zauważono w Alpach, gdzie często można go było zarejestrować jedynie na wyższych wysokościach, bliżej ekotonu (Lotter i in., 1992; Welten, 1982). Z kolei stanowiska zawierające sekwencje osadów późnoglacialnych, w których starszy dryas wyróżniono na podstawie chronologii absolutnej jako GI-1d (Rasmussen i in., 2014), mimo iż występują dość rzadko, charakteryzują się różnymi położeniami topograficznymi zróżnicowanymi przy tym paleośrodowiskowo (Ammann i in., 2013; Bos i in., 2013, 2017; Feurdean i Bennike, 2004; Moska i in., 2022).

5.6. Refugia roślin ciepłolubnych

W czasie ostatniego zlodowacenia, zasięg występowania wielu gatunków drzew liściastych strefy umiarkowanej ograniczony był do lokalnych refugium położonych na średnich wysokościach rejonów górskich Półwyspu Iberyjskiego, Apenińskiego i Bałkańskiego (refugia południowoeuropejskie), zaś na obszarze Europy Środkowej i Wschodniej obejmował niewielkie populacje, określane również jako tzw. krypto-refugia (Birks i Willis, 2008). Pomimo, iż dane pyłkowe wskazują na nieprzerwane regionalne występowanie mezofilnych drzew liściastych strefy umiarkowanej na obszarze Karpat w późnym pleniglacjale, wciąż brakuje danych makroszczałkowych do potwierdzenia ich lokalnego występowania; spodziewane są one najbardziej w miejscach o wilgotnym mezoklimacie na stokach górskich o średniej wysokości (Magyari i in., 2014). Analiza makroszczałków roślin jest podstawową metodą do zweryfikowania wyników analizy pyłkowej i wskazuje na istnienie refugium *in situ*, należy jednak również pamiętać o ograniczeniach tej metody (Birks, 2003). Brak makroszczałków ciepłolubnych drzew liściastych w osadzie nie koniecznie oznacza brak występowania ciepłolubnej roślinności w otoczeniu zbiornika sedymentacyjnego, gdyż makroszczałki takich roślin mają – w porównaniu do pyłku – mniejsze zdolności do rozprzestrzeniania się i bycia deponowanymi w centrum basenu sedymentacyjnego

jeziora/torfowiska, jak również części wegetatywne tych roślin słabo się zachowują i są trudne w identyfikacji (Birks, 2003).

Drzewa i krzewy liściaste, w tym również ciepłolubne, przetrwały w centralnej i wschodniej Europie pomiędzy 42 tys. a 19 tys. lat cal BP (Willis i Van Andel, 2004). Przykładowo, na stanowisku Bulhary w Czechach, spektra pyłkowe oprócz lasów iglastych, wskazują na rozproszone występowanie drzew liściastych strefy umiarkowanej: *Ulmus*, *Acer*, *Corylus*, *Quercus* i *Tilia* (Rybníčková i Rybníček, 1991). Na obszarze Rumuni drzewa liściaste były obecne już przed 14 700 lat cal BP, stąd ten region mógł stanowić dla nich obszar refugialny (Feurdean i in., 2007). W czasie późnego glacjału (szczególnie pomiędzy 13 200 an 12 900 lat cal BP) *Ulmus* występował w Karpatach Rumuńskich na niskich i średnich wysokościach, zaś *Quercus*, *Tilia*, *Fraxinus* i *Corylus* skupiały się prawdopodobnie w kilku odizolowanych lokalizacjach (Feurdean i in., 2007). W Południowych Karpatach Rumuńskich, refugialne populacje *Quercus*, *Ulmus*, *Carpinus betulus* oraz *Fagus sylvatica* były obecne w regionie w okresie LGM (Last Glacial Maximum). *Ulmus* rozprzestrzenił się odpowiednio od 15 200 do 14 400 lat cal BP na stokach południowych, zaś na północnych od 14 300 do 13 850 lat cal BP; ekspansja *Quercus* datowana jest na 13 900 lat cal BP (Magyari i in., 2018). Ponadto, badając transekty S-N w południowych Karpatach Rumuńskich, wykazano, iż *Abies alba*, *Larix decidua* i *Fagus sylvatica*, a więc gatunki występujące w chłodniejszych warunkach klimatycznych, wykazują preferencje do przetrwania i ekspansji na północnych stokach, podczas gdy ciepłolubne *Corylus avellana* i *Carpinus betulus* na stokach południowych (Magyari i in., 2018).

Obszary osuwisk charakteryzujące się dużą różnorodnością form terenu, gleb i stosunków wodnych wpływają na powstawanie mozaiki siedlisk o wysokiej bioróżnorodności (Alexandrowicz i Margielewski, 2010). Wykazano, że również na początku holocenu strefy osuwiskowe zewnętrznych Karpat zachodnich mogły stwarzać dogodne warunki do występowania refugium roślinności ciepło- i wilgociolubnej (*Tilia*, *Corylus*, *Ulmus* i *Acer*), szczególnie w swoich wyższych nasłonecznionych partiach (Šímová i in., 2019). We wcześniejszej analizie palinologicznej późnoglacialnych osadów torfowiska Kotoń, na głębokości ok. 450–400 cm zarejestrowano występowanie pyłku roślin ciepłolubnych: *Corylus avellana*, *Ulmus*, *Tilia* undiff., *Quercus*, *Carpinus betulus* oraz pyłku drzew preferujących chłodniejszy klimat: *Fagus sylvatica* i *Abies alba*, o udziałach procentowych około lub poniżej 1% (Margielewski, 2001b; Margielewski i in., 2003). Dla podobnego odcinka czasowego, w osadach stanowiska Klaklowo (w interwale ok. 340–280 cm) podczas wcześniejszych badań

zarejestrowano jedynie śladowe ilości pyłku *Corylus* (Margielewski, 2001a). Dla Kotonia obecność pyłku ciepłolubnych taksonów drzew została powiązana z możliwą redepozycją, dalekim transportem lub bliskością refugium (Margielewski i in., 2003). Pyłek roślin termofilnych został też odnaleziony w osadach późnoglacialnych torfowiska Na Grelu w Kotlinie Orawsko-Nowotarskiej (Margielewski i in., 2022a).

5.7. Poziomy tefry w osadach

Znaczna długość sekwencji późnego glacjału w profilach osadów torfowisk Kotoń i Klakłowo stwarza warunki do analizy występowania poziomów tefry (horyzontów z pyłami wulkanicznymi) pochodzących z dalekiego transportu z erupcji wulkanicznych w późnym glacialu w Europie (Bronk Ramsey i in., 2015). Do późnoglacialnych horyzontów tefry należą: Neapolitan Yellow Tuff (NYT), Laacher See Tephra (LST), Vedde Ash (Bronk Ramsey i in., 2015), a także potencjalnie tefra pochodząca z erupcji wulkanu Sfinta Ana (Juvigné i in., 1994). Wymienione poziomy tefry, poza Sfintą Aną, stanowią ważne markery chronostratygraficzne w osadach późnego glacjału i nie zostały dotąd udokumentowane w zachodniej części Karpat – znalezienie ziaren tefry pochodzących z erupcji NYT, LST lub Vedde Ash mocno zmodyfikowałoby obecną mapę zasięgu pyłów wulkanicznych powstałych wskutek aktywności wulkanów w późnym glacialu (Bronk Ramsey i in., 2015). Odkrycie horyzontów tefry może otworzyć również pole działania w kontekście innych torfowisk górskich w Karpatach oraz wzajemnej korelacji osadów w nich zdeponowanych, szczególnie w aspekcie rekonstrukcji paleośrodowiskowych i paleoklimatycznych.

Tefra NYT (erupcje strefy wulkanicznej Campi Flegrei, S Włochy, $14\,190 \pm 680$ lat cal BP) została udokumentowana w południowej Europie, z zasięgiem do SE Alp (jezioro Längsee w Austrii) (Schmidt i in., 2002) będącym najbliższym położonym stanowiskiem w stosunku do zewnętrznych Karpat zachodnich. Występowanie Laacher See Tephra (erupcja wulkanu Laacher See w górach Eifel, w zachodnich Niemczech, $12\,880 \pm 40$ lat cal BP) zostało zarejestrowane na terytorium SW Polski (przy granicy z Niemcami) blisko miejscowości Węgliny (Housley i in., 2013; Jurochnik i Nalepka, 2013) oraz w osadach dwóch torfowisk w NW części Pomorza (Juvigné i in., 1995). LST została również rozpoznana w warwowych osadach późnoglacialnych Jeziora Czechowskiego w północno-środkowej Polsce (Wulf i in., 2013). Poza granicami Polski, najbliższe względem Karpat stanowisko z osadami późnoglacialnymi z poziomem LST, to Las Bawarski w sąsiedztwie granicy Niemiec z

Czechami (Kletetschka i in., 2019). Tefra Vedde Ash (erupcja wulkanu Katla, Islandia, $12\ 066 \pm 42$ lat cal BP) jest szeroko rozprzestrzeniona m.in. w Skandynawii, Zachodniej Europie i północnej Rosji (Saxby i in., 2020). Nie została dotychczas odnaleziona na terytorium Polski ani w obrębie Karpat (Lane i in., 2012), jakkolwiek jej daleki południowy zasięg został potwierdzony w osadach jeziora Lake Bled, w Alpach Julijskich w Słowenii (Lane i in., 2011). Tefra pochodząca z erupcji wulkanów Islandii, w tym z Katli, ale zidentyfikowana w horyzontach innego wieku niż Vedde Ash została również znaleziona w jeziorze Węgliny (Housley i in., 2013). Tefra z erupcji wulkanu Sfinta Ana (Karpaty Rumuńskie) posiada niepotwierdzony wiek erupcji $10\ 700 \pm 180$ lat uncal BP (Juvigné i in., 1994), i wg. innych autorów erupcja ta jest znacznie starsza, ok. 42–35 tys. lat (Moriya i in., 1996; Szakács i in., 2002). Poza miejscem jej pierwotnego stwierdzenia, brak jest jednak innych udokumentowanych stanowisk z osadami zawierającymi tefrę z erupcji wulkanu Sfinta Ana o wieku $10\ 700 \pm 180$ lat uncal BP.

6. Cel pracy i hipotezy badawcze

Głównym celem badawczym pracy jest:

1a: Rozpoznanie powszechnych lub regionalnych zmian klimatycznych w późnym glacie (15–11,7 tys. lat) w lokalnym zapisie środowiska sedymentacyjnego torfowisk osuwiskowych, położonych w różnych pozycjach hipsometrycznych (Kotoń – w części podszczytowej stoku, Klakłowo – w strefie dolinnej zbocza).

1b: Określenie zmian w składzie makroszczątków roślin w obrębie dwóch profili, pobranych z różnych stref tego samego torfowiska, które pozwolą określić, w jakim stopniu analiza jednego profilu jest reprezentatywna dla danego torfowiska, a szczególnie w późnym glacie, charakteryzującym się stosunkowo niewielką różnorodnością biologiczną.

1c: Określenie zmian roślinności w starszym dryasie tj. krótkotrwałym ochłodzeniu (190 lat, 13540–13350 cal. BP) w późnym glacie, którego zapis osadów w torfowisku Kotoń i Klakłowo osiąga znaczną miąższość wynoszącą 0,5 m.

Drugorzędnym celem badawczym pracy jest:

2a: Weryfikacja hipotezy występowania w późnym glacie (interfaza bølling) refugium roślin

termofilnych na obszarze osuwiska Kotoń, identyfikowanych tu dotychczas w oparciu o analizę palinologiczną, przeprowadzona za pomocą analizy makroszczątków roślin.

2b: Analiza i identyfikacja (w przedziałach głębokości wytypowanych w oparciu o model wiek-głębokość) poziomów mikrotefry, związanych z erupcjami wulkanów w późnym glacie: Neapolitan Yellow Tuff (NYT), Laacher See Tephra (LST), Sfanta Ana Tephra (SAT) i Vedde Ash Tephra (VAT).

Hipotezy badawcze są następujące:

- Zweryfikowanie za pomocą analizy makroszczątków występowania w późnym glacie na osuwisku Kotoń (w warunkach niszy mikroklimatycznej) refugium roślin ciepłolubnych (lipa, dąb, leszczyna i inne taksony o wyższych wymaganiach klimatycznych) oraz występowania buka i jodły, na które wskazuje wykonana tu dotychczas analiza palinologiczna.
- Zmiany klimatyczne w późnym glacie inaczej zaznaczyły się w obrębie stanowisk o ekspozycji południowej, posadowionych w obrębie szczytowych partii gór, inaczej zaś w obrębie stanowisk o ekspozycji północnej, posadowionych w strefach dolinnych.
- Analiza makroszczątków przeprowadzona jedynie w obrębie jednego profilu może nie być reprezentatywna dla całego zbiornika sedymentacyjnego.

7. Teren badań

7.1. Lokalizacja, geologia i geomorfologia

Według fizyczno-geograficznego podziału Polski, obszar badań położony jest na południu Polski w mezoregionie Beskidu Makowskiego, który jest częścią podprowincji Zewnętrznych Karpat Zachodnich (Solon i in., 2018) (Figura 1). Karpaty zewnętrzne zbudowane są ze skał fliszowych (turbidytów krzemionkowo-ilastych, a sporadycznie również ze skał węglanowych i krzemionkowych), których wiek powstawania obejmuje okres od późnej jury do wczesnego miocenu (Książkiewicz, 1972). Obszar badań znajduje się w podjednostce Siar, należącej do jednostki magurskiej: jednej z płaszczowin zewnętrznych Karpat zachodnich (Książkiewicz i in., 2016). Torfowiska osuwiskowe Kotoń i Klakłowo powstały w obrębie pasma Koskowej Góry w Beskidzie Makowskim. Stanowisko Kotoń znajduje się w strefie wierzchowinowej pasma, pomiędzy wzniesieniami Kotonia (857 m n.p.m.) i Pękałówki (839

m n.p.m.). na wysokości 739 m n.p.m., ma ekspozycję południową i jest położone blisko grzbietu, ponad strefą źródłiskową potoku Rusnaków, będącego lewym dopływem Krzczonówki. Stanowisko Klaklowo położone jest na wysokości 466 m n.p.m., ma ekspozycję północną, jest umiejscowione w przydolinnej strefie zbocza pasma Koskowej Góry i znajduje się w strefie źródłiskowej jednego z lewych dopływów Raby. Odległość między stanowiskami wynosi ok. 1900 m, a różnica wysokości: 273 m.

7.2. Klimat

Na podstawie pomiarów z lat 1991–2021 (Climate Data, 2024) klimat wsi Zawadka i Stróża (położonych odpowiednio pod osuwiskami Kotoń i Klaklowo) jest ciepły i umiarkowany, ze znaczną ilością opadów, na co wpływa surowy teren górski. Średnia temperatura roczna wynosi 7,9°C, a średnia suma opadów 1063 mm. W rejonie Beskidu Makowskiego wiosna jest długa, chłodna i deszczowa, natomiast jesień jest również długa, ale sucha, z częstymi wahaniami temperatury. Podobnie jak w regionach sąsiednich, w dolinach rzecznych występują inwersje temperatury.

7.3. Charakterystyka osuwisk

Osuwisko Kotoń rozwinęło się w gruboławicowych piaskowcach magurskich (budujących znaczną część pasma Koskowej Góry) i ma kształt rozległego klina z dwiema liniowymi skarpami głównymi, między którymi występuje wypłaszczenie koluwalne osuwiska. Strefa osuwiskowa Klaklowo ma z kolei amfiteatralny kształt. Podłoże w rejonie półkolistej skarpy głównej i położonego pod nią zagłębienia (torfowisko Klaklowo) tworzą skały fliszowe wieku eoceńskiego (Książkiewicz i in., 2016): łupki, łupki pstre i cienkoławicowe piaskowce warstw hieroglifowych, łupki pstre oraz piaskowce i zlepieńce gruboławicowe oraz łupki (piaskowce pasierbieckie dolne oraz osieleckie). Obszar powyżej osuwiska, podobnie jak w przypadku Kotonia, zbudowany jest z piaskowców warstw magurskich.

7.4. Zagłębienia pod skarpą główną, hydrologia i osady torfowiskowe

W przypadku osuwiska Kotoń, zagłębienie stanowiące misę torfowiska (o szerokości ok. 40 m i długości ok. 90 m) rozwinęło się u podnóża zachodniej skarpy głównej osuwiska i ma podłużny kształt (Figura 1 E). Od wschodu jest ono otoczone wałem koluwalnym, co doprowadziło do wypełnienia zagłębienia późnoglacialnymi i holoceniowymi osadami organiczno-minerogenicznymi o miąższości do 500 cm. Obecnie, z wyjątkiem potoku Rusnaków, który wypływa w dolnej części osuwiska, w strefie osuwiskowej Kotonia brak jest stałych cieków, szczególnie tych spływających ze skarpy głównej i zboczy do zagłębienia pod skarpą główną, aczkolwiek prawdopodobne jest występowanie cieków okresowych (Figura 1 E).

W przypadku osuwiska Klakłowo, zagłębienie pod skarpą główną (o szerokości ok. 40 m i długości ok. 100 m), ze względu na półkolistą skarpę główną osuwiska graniczącą z nim od południa, ma kształt lekko wygięty w kierunku południowym (Figura 1 D). Od północy zagłębienie otoczone jest wałem koluwalnym, który we wschodniej części przecięty jest stałym ciekami wypływającym z misy torfowiska do doliny potoku będącego dopływem Raby. Obecnie zagłębienie pod skarpą główną osuwiska Klakłowo, wypełniają osady organiczno-minerogeniczne wieku późnoglacialnego i holoceniowego o miąższości do 367 cm. Torfowisko Klakłowo zasilane jest także kilkoma małymi (stałymi i okresowymi) ciekami wodnymi spływającymi ze skarpy głównej do zagłębienia osuwiskowego (Figura 1 D).

7.5. Gleba i roślinność

Współcześnie stoki Beskidu Makowskiego pokryte są głównie glebami brunatnymi (Bank Danych o Lasach, 2025). Średnia roczna długość okresu wegetacyjnego wynosi od 220 do 230 dni (Tomczyk i Bednorz, 2022). W bezpośrednim sąsiedztwie torfowisk Kotoń i Klakłowo otaczające je zbocza i formy osuwiskowe są zalesione (buczyna karpacka), głównie przez jodłę (*Abies alba*) i buka (*Fagus sylvatica*) z domieszką świerka (*Picea* sp.). Brzoza (*Betula* sp.), topola (*Populus* sp.) i modrzew (*Larix* sp.) występują lokalnie wokół torfowisk, natomiast krzewy wierzby (*Salix* sp.) rosną również w obrębie torfowisk. Część podmokłych brzegów cieków w okolicy Klakłowa porośnięte są olszą (*Alnus* sp.).

8. Metody badań

8.1. Pobór materiału do badań

Rdzenie osadów nawiercono i pobrano świdrem INSTORF (średnica 8 cm) z torfowiska Kotoń (49°46'5.12"N; 19°54'12.96"E, 739 m n.p.m.) i torfowiska Klaklowo (N 49°46,772'; E 19°55,383'; 466 m n.p.m.). Rdzenie główne pobrano w miejscach o największej miąższości osadów, odpowiednio 500 i 367 cm (wiercenia G, Figura 1 D, E, F i G). W celu realizacji celów badawczych nr 1b oraz 2a pobrano również rdzenie boczne ze stref marginalnych zagłębień osuwiskowych, po dwa rdzenie boczne na stanowisko. Dla Klaklowa były to: rdzeń boczny Klaklowo B1 (267 cm) i oraz dodatkowy rdzeń boczny Klaklowo B2 (analizom poddano jedynie fragment dolnej, późnoglacialnej części tego profilu, 368–250 cm) (Figura 1 D i F), zaś dla Kotonia: rdzeń boczny Kotoń B1 (250 cm) oraz dodatkowy rdzeń boczny Kotoń B2 (analizom poddano jedynie fragment dolnej, późnoglacialnej części tego profilu 400–300 cm) (Figura 1 E i G). Pobranie kolejnych rdzeni bocznych (B2) wykonane zostało dodatkowo (ponadprogramowo) w stosunku do zakresu prac określonych w projekcie z uwagi na konieczność zwiększenia możliwości odnalezienia makroszczałków roślin ciepłolubnych. Prace terenowe zostały wykonane przez mgr inż. Jolantę Pilch, dr hab. inż. Włodzimierza Margielewskiego, prof. IOP PAN (promotora) oraz dr Krzysztofa Buczka z IOP PAN. Rdzenie następnie opróbowano, zaś materiał z próbek poddano analizie makroszczałków roślin, analizie pyłkowej i datowaniu radiowęglowemu (rdzenie główne i boczne) oraz analizie strat prażenia, uziarnienia i geochemicznej (tylko rdzenie główne).

8.2. Datowanie radiowęglowe i opracowanie modelu wiek-głębokość

Materiał do datowania radiowęglowego metodą AMS (Acceleration Mass Spectrometry) pozyskano równocześnie z analizą makroszczałków roślin z próbek sekwencji osadów Klaklowa i Kotonia w przedziale głębokości odpowiednio, 367–68 cm i 440–77 cm (rdzenie główne). Materiał obejmował owoce, nasiona, liście, igły (wyłącznie roślin lądowych) i łodygi mchów. Datowania zostały wykonane przez Laboratorium Datowań Bezwzględnych w Krakowie (we współpracy z Center For Applied Isotope Studies, University of Georgia, U.S.A.) oraz laboratorium Beta Analytic, Inc. Miami, Florida, U.S.A. Łącznie wykonano osiemnaście dat radiowęglowych dla rdzeni głównych: 12 dla osadów torfowiska Klaklowo i 6 dla osadów torfowiska Kotoń. Wszystkie otrzymane daty radiowęglowe skalibrowano w programie OxCal

v. 4.4.4 (Bronk Ramsey, 2021, 2009) z wykorzystaniem krzywej kalibracyjnej IntCal20 (Reimer i in., 2020).

Dla rdzeni głównych osadów torfowisk osuwiskowych Klakłowo i Kotoń opracowano chronologie absolutne poprzez konstrukcję bayesowskich modeli wiek-głębokość. Dla obu badanych stanowisk modelowanie przeprowadzono w programie OxCal w wersji 4.4.4 (Bronk Ramsey, 2021, 2009) z zastosowaniem funkcji P_sequence, interpolacji = 2 (0,5 cm), parametrów $k_0 = 1$ i $\log_{10}(k/k_0) = U(-1,1)$ oraz krzywej kalibracyjnej IntCal20. Ponadto, na głębokościach, gdzie zostały zarejestrowane charakterystyczne zmiany w litologicznych i/lub biotycznych wskaźnikach, zastosowano polecenie *Boundary command*. Uzyskano średnią (μ) wartość modelowanego wieku (zaokrągloną do części dziesiętnych, wyrażoną w latach cal BP) i tempo sedymentacji (wyrażone w mm rok^{-1}). Modele wiek-głębokość zostały opracowane przez mgr inż. Jolantę Pilch przy wsparciu merytorycznym dr Krzysztofa Buczka z IOP PAN.

Dla rdzeni bocznych datowano łącznie 16 próbek: Klakłowo B1 – 7, Klakłowo B2 – 1, Kotoń B1 – 4, Kotoń B2 – 4 próbki (Tabela 1). Ponadto, w końcowym etapie realizacji projektu, w celu stworzenia możliwości dalszego doprecyzowania modeli wiek-głębokość dla wybranych poziomów głębokości rdzeni głównych, uzyskano jedną dodatkową datę radiowęglową dla Klakłowa i dwie dla Kotonia (Tabela 1). Wspomniane datowania zostały wykonane przez Laboratorium Datowań Bezwzględnych w Krakowie.

8.3. Analiza strat prażenia oraz określenie typu torfu

Analiza strat prażenia (loss on ignition, LOI) została przeprowadzona przez mgr inż. Jolantę Pilch pod opieką naukową dr hab. inż. Włodzimierza Margielewskiego. W przypadku analizy strat prażenia interwał pobierania próbek wynosił 2,5 cm. Proces wyprażenia przeprowadzono w piecu muflowym w temperaturze 550°C, zgodnie ze standardową procedurą opisaną przez Heiri i in. (2001). Ubytek masy wyprażonego osadu organicznego, wyrażony w %, przedstawiono na wykresach strat prażenia. Gatunek torfu przyjęto zgodnie z wcześniejszymi badaniami torfowisk osuwiskowych Klakłowo i Kotoń (Margielewski, 2001a, 2001b; Margielewski i in., 2003), w oparciu o analizę tkanek roślinnych, bazując na klasyfikacji torfu opracowanej przez Tołpa i in. (1967).

8.4. Analiza makroszczątków roślin

Analiza makroszczątków roślin została przeprowadzona przez mgr inż. Jolantę Pilch pod opieką naukową dr hab. Renty Stachowicz-Rybki (drugiego promotora) z Instytutu Botaniki im. W. Szafera PAN w Krakowie. Główny rdzeń osadów torfowiska Kotoń został opróbowany z większą rozdzielczością (próbki o miąższości 2,5 cm) w przedziale głębokości 500–300 cm (oraz dodatkowo w interwałach głębokości 270–260 i 80–70 cm) oraz z mniejszą rozdzielczością (próbki o miąższości 2,5 cm analizowane co 5 cm) w przedziale głębokości 300–0 cm. W przypadku torfowiska Klakłowo, główny rdzeń osadów opróbowano z większą rozdzielczością (próbki o miąższości 2,5 cm) w interwale głębokości 367–250 cm (zastosowano również gęstsze próbkowanie pomiędzy 250 a 220 cm głębokości), natomiast interwał głębokości 250–0 cm opróbowano z mniejszą rozdzielczością (próbki o miąższości 2,5 cm analizowane co 5 cm). Dla materiału z rdzeni bocznych wykonano analizę makroszczątków roślin na próbkach o miąższości 2,5 cm pobranych z interwalem próbkowania 5 oraz 10 cm.

Materiał do analizy został rozlasowany w wodzie z dodatkiem KOH w celu usunięcia kwasów humusowych, a następnie delikatnie przemyty bieżącą wodą przez sito o średnicy oczek 200 µm. Oznaczenie taksonów na podstawie makroszczątków roślin (owoców, nasion, igieł, oospor) oraz – w znacznie mniejszym stopniu – zwierząt (np. gemmule, statoblasty, ephippia) przeprowadzono pod mikroskopem stereoskopowym Stemi 508 firmy ZEISS, przy powiększeniach 10–16x. Do identyfikacji wykorzystano kolekcję współczesnych diaspor i okazów flory kopalnej z Narodowej Kolekcji Bioróżnorodności Organizmów Współczesnych i Kopalnych zgromadzonych w Instytucie Botaniki im. W. Szafera PAN w Krakowie (Zielnik KRAM) oraz odpowiednie klucze, atlasy i publikacje (Aalto, 1970; Anderberg, 1994; Berggren, 1969, 1981; Birks, 2013; Cappers i in., 2012; Kats i in., 1965; Körber-Grohne, 1964, 1991; Kowalewski, 2014; Mauquoy i Van Geel, 2007; Velichkevich i Zastawniak, 2006, 2008). Nomenklaturę botaniczną roślin naczyniowych przyjęto zgodnie z Mirek i in. (2020), natomiast wskaźniki ekologiczne roślin zaczerpnięto głównie z pracy Zarzyckiego (2002). Określone taksony roślin i zwierząt pogrupowano w następujący sposób: drzewa, krzewy i krzewinki umieszczono razem, natomiast pozostałe rośliny naczyniowe wraz z Bryopsida i Characeae, podzielono według stopnia wilgotności siedliska (suche, świeże i wilgotne, torfowiskowe i wodne). Taksony zwierząt i inne typy szczątków przypisano do grupy „Others”. Za pomocą oprogramowania Tilia (Grimm, 1991) sporządzono diagramy makroszczątków dla obydwu stanowisk.

8.5. Analiza palinologiczna i analiza palinomorf niepyłkowych (NPPs)

8.5.1. Rdzenie główne

W niniejszych badaniach, dla głównych rdzeni osadów, wykorzystano wcześniejszy zbiór danych palinologicznych z torfowiska Kotoń (Margielewski, 2001b; Margielewski i in., 2003) (odległość od aktualnego miejsca wiercenia wynosi ok. 0,5 m) opracowanych przez dr hab. Andrzeja Obidowicza z Instytutu Botaniki im. W. Szafera PAN w Krakowie oraz nowo pozyskane dane palinologiczne i NPPs z torfowiska Klakłowo opracowane przez dr Katarzynę Korzeń.

W przypadku sekwencji osadów torfowiska Klakłowo (367–0 cm), próbki (około 1 cm³ osadu) pobrano w odstępach 5 cm i poddano standardowej procedurze laboratoryjnej stosowanej w analizie palinologicznej (Erdtman, 1960; Fægri i Iversen, 1989). Ilościowa analiza pyłku i NPPs (z użyciem tabletek *Lycopodium*) polegała na zliczeniu (pod mikroskopem świetlnym) ziaren pyłku drzew i krzewów do co najmniej 600 sztuk na próbkę. Identyfikację taksonomiczną pyłku przeprowadzono w oparciu o kolekcję współczesnych preparatów pyłkowych oraz odpowiednie klucze i atlasy (Beug, 2004; Moore i in., 1991; Reille, 1992). Palinomorfy niepyłkowe zidentyfikowano zgodnie z kluczami opracowanymi przez Van Geel (1978) oraz Van Geel i in. (1980, 2003, 2007).

W archiwalnym zbiorze danych pyłkowych z Kotonia (450–0 cm), interwał próbkowania wynosił ok. 10 cm dla przedziału głębokości 100–0 cm, natomiast poniżej 100 cm (dla osadów późnego glacjału) interwał próbkowania był mniejszy i wynosił ok. 5 cm. Preparatykę próbek przeprowadzono w oparciu o zmodyfikowaną metodę acetolizy Erdtmiana (Erdtman, 1943). Analiza ilościowa pyłku (z wykorzystaniem tabletek *Lycopodium*) polegała na zliczeniu (pod mikroskopem świetlnym) ziaren pyłku drzew i krzewów do co najmniej 500 na próbkę, z wyjątkiem osadów holocenijskich, w których liczba zliczonych ziaren wynosiła co najmniej 1000. Ponieważ archiwalny zbiór danych pyłkowych z osadów torfowiska Kotoń (450 cm) był krótszy o 0,5 m od rdzenia osadów pozyskanego w ramach bieżących badań (500 cm), w celu uzupełnienia tej luki, osady w interwale 500–450 cm z aktualnie uzyskanego rdzenia z torfowiska Kotoń został poddany analizie pyłkowej w sposób analogiczny do osadów torfowiska Klakłowo.

Bieżące dane palinologiczne uzyskane z torfowiska Klaklowo (367–0 cm) oraz wcześniejsze dane palinologiczne z torfowiska Kotoń (450–0 cm) zostały przeliczone w ujednolicony sposób na udziały procentowe każdego taksonu na podstawie sumy pyłku drzew, krzewów i krzewinek (AP – arboreal pollen) oraz roślin zielnych (NAP – non-arboreal pollen) określonej jako $\Sigma AP + \Sigma NAP = \Sigma P$. W zależności od stanowiska badań (KK – Klaklowo, KT – Kotoń), z sumy tej wykluczono następujące grupy: rośliny zarodnikowe (KK, KT), rośliny wodne (KT), pyłek nieoznaczalny (KT), pyłek skorodowany (KK) i palinomorfy niepyłkowe (KK, zaś w przypadku KT – tylko glony *Pediastrum*). Częstość występowania taksonów tych grup obliczono na podstawie wzoru $\Sigma P + \text{suma ziaren z odpowiadającej grupy} = 100\%$. Cyperaceae włączono do grupy roślin zielnych, zgodnie z oryginalnym diagramem pyłkowym z Kotonia (Margielewski i in., 2003). Wszystkie obliczenia i diagramy palinologiczne dla rdzeni głównych zostały wykonane przez mgr. inż. Jolantę Pilch za pomocą oprogramowania Tilia (Grimm, 1991). W przypadku diagramu pyłkowego Kotonia przedstawiono tylko najważniejsze taksony roślin.

8.5.2. Rdzenie boczne

Analizę palinologiczną rdzeni bocznych z obydwu torfowisk przeprowadził w ramach bieżących badań dr Artur Górecki z Instytutu Botaniki Uniwersytetu Jagiellońskiego. Analiza palinologiczna dla dodatkowych rdzeni bocznych Klaklowo B2 oraz Kotoń B2 (fragmenty dolnych partii tych rdzeni) wykonana była w ramach dotacji dla młodych naukowców Instytutu Ochrony Przyrody PAN.

Z profili bocznych pobrano łącznie 173 próbek do analiz palinologicznych: po 1 cm³ w przypadku torfów oraz po 3 cm³ w przypadku iłów, pyłów i mułków. Liczba próbek wynosiła odpowiednio: Klaklowo B1 – 64, Klaklowo B2 – 23, Kotoń B1 – 63 oraz Kotoń B2 – 20. Próbkę pobierano w odstępach co 5 cm i w razie potrzeby dogęszczano. Próbkę z profili Klaklowo B2 i Kotoń B2 przygotowano zgodnie z metodyką opracowaną przez Berglund i Ralską-Jasiewiczową (1986), z zastosowaniem procedury acetolizy według Erdtmanna (1960). W przypadku profili Klaklowo B1 i Kotoń B1 zrezygnowano z użycia kwasu fluorowodorowego (HF), natomiast pyłek ekstrahowano metodą separacji w cieczy o dużej gęstości, z wykorzystaniem roztworu chlorku cynku (ZnCl₂) o gęstości 1,88 g/cm³, zgodnie z procedurą Nakagawa i in. (1998). Identyfikację ziaren pyłku oraz palinomorf niepyłkowych prowadzono

przy użyciu mikroskopu świetlnego przy powiększeniu 400×, korzystając z kluczy oraz internetowych baz danych (Beug, 2004; PalDat: Palynological Database, 2000; Shumilovskikh i in., 2022). W większości przypadków zliczano do 500 ziaren pyłku roślin drzewiastych (AP) i zielnych (NAP), z wyłączeniem taksonów wodnych i szuwarowych. W przypadku niskiej frekwencji pyłku liczone do 300 ziaren lub analizowano całość materiału w próbce. Wyniki przedstawiono w postaci diagramów palinologicznych opracowanych w programie POLPAL (Nalepka i Walanus, 2003). Diagramy graficzne przygotowano z wykorzystaniem środowiska Rstudio (Posit Team, 2025) i pakietu riojaPlot (Juggins, 2022a).

8.6. Analiza uziarnienia (granulometryczna)

Analizę granulometryczną przeprowadzono metodą dyfrakcji laserowej na granulometrze Mastersizer 3000 (Malvern Panalytical, Wielka Brytania) w laboratorium geomorfologicznym Instytutu Geografii i Gospodarki Przestrzennej, Uniwersytetu Jagiellońskiego w Krakowie, we współpracy z dr Mateuszem Stolarczykiem oraz dr Łukaszem Musielokiem. Zawartość frakcji osadu, rodzaj osadu oraz parametry statystyczne rozkładu granulometrycznego (średnią wielkość ziarna, odchylenie standardowe, skośność i kurtozę) według metody graficznej Folka i Warda (1957) obliczono w programie GRADISTAT (Blott i Pye, 2001). Mechanizmy transportu i depozycji osadów określono na podstawie diagramu C-M (Passega i Byramjee, 1969). Analizie granulometrycznej poddano odcinki głębokości rdzeni głównych torfowisk Klaklowo i Kotoń zdominowane przez osady minerogeniczne.

8.7. Analiza potencjalnych poziomów tefry związanych z erupcjami wulkanów w późnym glacie

Analiza i identyfikacja poziomów tefry, związanych z erupcjami wulkanów w późnym glacie, została przeprowadzona dla: Neapolitan Yellow Tuff (NYT), związanej z erupcją wulkanów obszaru Campi Flegrei w pobliżu Neapolu, Włochy oraz Laacher See Tephra (LST), związanej z erupcją wulkanu Laacher See w górach Eifel, W Niemcy (Tabela 3). Zaniechana została planowana analiza i identyfikacja poziomów mikrotefry Vedde Ash, związanych z erupcją wulkanu Katla na Islandii, oraz osadów wulkanicznych pochodzących z erupcji wulkanu Sfinta Ana w Karpatach Wschodnich na terytorium Rumunii (Tabela 3). W pierwszym

przypadku podyktowane to było małym prawdopodobieństwem dotarcia pyłu wulkanicznego do obszaru badań, tj. Zachodnich Karpat Zewnętrznych (Bronk Ramsey i in., 2015), zaś w drugim niepotwierdzonym wiekiem erupcji Sfintej Any, $10\,700 \pm 180$ lat uncal BP (Juvigné i in., 1994), która wg. innych autorów jest znacznie starsza, ok. 42–35 tys. lat (Moriya i in., 1996; Szakács i in., 2002). Daty erupcji NYT i LST przyjęto w oparciu o zaktualizowane (z użyciem najnowszych dostępnych metod oraz radiowęglowych krzywych kalibracyjnych: IntCal13 i Marine13) oszacowania wieku tych erupcji (rekomendowany model 2, Bronk Ramsey i in., 2015). Dla zakresów czasowych tych erupcji, w oparciu o modele wiek-głębokość skonstruowane dla sekwencji osadów torfowisk Kotoń i Klakłowo, zostały wytypowane przedziały głębokości, z których pobrano próbki do analizy potencjalnych poziomów tefry (Tabela 3).

Preparatyka próbek została przeprowadzona we współpracy z dr Joanną Sławińską w laboratorium chemicznym Instytutu Nauk o Morzu i Środowisku Uniwersytetu Szczecińskiego, w oparciu o procedurę opracowaną przez Blockley i in. (2005). Odpowiednie fragmenty rdzeni osadów opróbowano w interwałach co 1 cm dla tefry LST i 10 cm dla tefry NYT (uśredniona reprezentacja osadu; próbki co 1 cm dla NYT zostały zachowane na przyszłe dokładniejsze analizy w przypadku znalezienia ziaren tefry). Otrzymane próbki poddano działaniu roztworu 10% HCl (usuwanie węglanów) oraz separacji na frakcje za pomocą cieczy ciężkiej SPT (sodium polytungstate). W efekcie otrzymano frakcję osadu o gęstości $2,5 \text{ g/cm}^3$ potencjalnie zawierającą ziarna tefry, którą następnie poddano wstępnej analizie i identyfikacji z użyciem mikroskopu polaryzacyjnego. Pod opieką merytoryczną dr J. Sławińskiej, mgr inż. J. Pilch przeprowadziła pilotażową preparatykę i identyfikację tefry dla fragmentu poziomu NYT (330–342,5 cm) z profilu Klakłowa, zaś pozostałe przedziały zostały przeanalizowane przez dr J. Sławińską.

8.8. Dodatkowe analizy geochemiczne

Dodatkowe (ponadprogramowe w stosunku do zakresu projektu) analizy geochemiczne zostały wykonane dla dolnych części sekwencji osadów torfowisk Klakłowo i Kotoń (interwały głębokości odpowiednio: 350–250 cm i 500–300 cm, próbkowanie co 2,5 cm) w Laboratorium Gleboznawczym Pracowni Gleboznawstwa i Geografii Gleb, w Instytucie Geografii i Gospodarki Przestrzennej Uniwersytetu Jagiellońskiego w Krakowie, we współpracy z dr Mateuszem Stolarczykiem oraz dr Łukaszem Musielokiem (oznaczenia zawartości CaCO_3 ,

SOC, TN, P-PO₄, N-NO₃ oraz N-NH₄) oraz Zakładzie Spektrometrii Mas, Instytut Fizyki Jądrowej PAN w Krakowie we współpracy z dr inż. Dariuszem Salą (oznaczenia zawartości Ca, Mg, K, Na, Fe, Mn, Ni, Cu, Zn, Pb).

Oznaczenia zawartości CaCO₃, SOC, TN, P-PO₄, N-NO₃ oraz N-NH₄. Zawartość węglanów (równoważnik CaCO₃ uzyskany ze stężenia CO₂ uwolnionego w reakcji z 10% HCl) określono metodą objętościową Scheiblera (Loeppert i Suarez, 1996). Ponadto wykorzystano zestaw wskaźników geochemicznych standardowo stosowanych w badaniach gleb (Wang i in., 2022). Całkowitą zawartość węgla (TOC) oraz azot całkowity (TN) określono metodą suchego spalania za pomocą analizatora pierwiastkowego Vario Micro Cube CHN z detekcją TCD (Elementar Analysensysteme GmbH, Langenselbold, Niemcy) (Nelson i Sommers, 1996). W przypadku większości próbek (ze względu na brak węglanów) przyjęto, że całkowita zawartość węgla odpowiada zawartości SOC. Jednak w przypadku obecności węglanów, zawartość SOC obliczono, odejmując zawartość węgla nieorganicznego ($eqCaCO_3 \times 0,12$) od całkowitej zawartości węgla.

Zawartość nietrwałych form mineralnego fosforu (P-PO₄), rozpuszczalnych w wodzie dejonizowanej, mierzono metodą spektrofotometryczną przy długości fali 550 nm (Levy i Schlesinger, 1999). Zawartość azotu azotanowego (N-NO₃) w 1% roztworach K₂SO₄ oznaczano przy użyciu kwasu fenylodisulfonowego i pomiarze absorbancji przy długości fali 410 nm (Gotkiewicz, 1983). Zawartość azotu amonowego (N-NH₄) w 1% roztworach K₂SO₄ oznaczano przy użyciu bezpośredniej reakcji Nesslera i pomiarze absorbancji przy długości fali 436 nm (Gotkiewicz, 1983). Zawartość P-PO₄, N-NO₃ i N-NH₄ oznaczano w materiale stałym próbki (woda porowa nie była badana). Chociaż zawartość frakcji P i N w osadach torfowisk podlega różnym procesom syn- i postdepozycyjnym (Salmon i in., 2021), przeprowadzono jakościowe badania potencjalnego związku z innymi danymi paleoekologicznymi. Obliczono stosunki N-NO₃/N-NH₄ w celu rekonstrukcji poziomu natlenienia osadów (Gotkiewicz, 1973).

Oznaczenia zawartości Ca, Mg, K, Na, Fe, Mn, Ni, Cu, Zn, Pb. próbki suszono w temperaturze 105 ± 5 °C w suszarce próżniowej (Alpina EG40, Polska) przez 24 godziny, a następnie umieszczono w piecu muflowym, gdzie były wyprażane w temperaturze 600 °C przez kolejne 6 godzin. Dokładnie odważone ok. 200 mg materiału rozpuszczono za pomocą stężonych kwasów (HF i HNO₃) w temperaturze 180 °C w zamkniętych pojemnikach PTFE w systemie do mineralizacji mikrofalowej (PreeKem M6). Po schłodzeniu próbki przefiltrowano w celu uniknięcia zablokowania systemu wprowadzania próbki i rozcieńczono do objętości

końcowej (50 ml). Do oznaczania pierwiastków (Ca, Mg, K, Na, Fe, Mn, Ni, Cu, Zn, Pb) w analizach geochemicznych użyto urządzenia Agilent 8900 Triple Quadrupole ICP-MS (Agilent Technologies, USA). Zakłócenia izobaryczne zredukowano dzięki zastosowaniu zintegrowanej komory zderzeniowo-reakcyjnej w helu, jako gazie kolizyjnym.

8.9. Analizy statystyczne

Analiza skupień z ograniczeniem stratygraficznym (stratigraphically constrained cluster analysis by the method of incremental sum of squares, CONISS, Grimm, 1987) została przeprowadzona w oparciu o wyniki analizy makroszczątków roślin i palinologicznej, w celu uzyskania odpowiednio wydzielen LMAZ (local macrofossil assemblage zones) i LPAZ (local pollen assemblage zones) dla sekwencji osadów torfowisk Klaklowo i Kotoń. W tym celu liczebności całkowite makroszczątków roślin zostały znormalizowane do tej samej objętości próbki osadu dla danego stanowiska (Klaklowo rdzeń główny do 20 cm³, Kotoń rdzeń główny do 16 cm³, Klaklowo rdzeń boczny B1 do 16 cm³, Klaklowo rdzeń boczny B2 do 14 cm³, Kotoń rdzeń boczny B1 do 18 cm³, Kotoń rdzeń boczny B2 do 18 cm³), natomiast w przypadku danych pyłkowych analizę skupień przeprowadzono w oparciu o udziały procentowe taksonów. Dla danych z rdzeni głównych liczbę statystycznie istotnych wydzielen LMAZ i LPAZ określono na podstawie broken-stick model (Bennett, 1996), zaś całość obliczeń przeprowadzono z wykorzystaniem pakietu Rioja (Juggins, 2022b) w wersji R 4.2.2 (R Core Team, 2022). Dla danych z rdzeni głównych ostateczne zakresy głębokości LMAZ, LPAZ i paleoekologicznych stadiów rozwoju torfowisk Klaklowo i Kotoń określono na podstawie wyników analizy skupień CONISS oraz wizualnej oceny diagramów makroszczątków roślin i diagramów palinologicznych. W przypadku danych palinologicznych z rdzeni bocznych, zony LPAZ wyznaczono korzystając z analizy skupień (CONISS) w programie riojaPlot (Juggins, 2022a).

W analizie reprezentatywności danych makroszczątkowych (cel badawczy 1b) skupiono się jedynie na jakościowym porównaniu rdzeni osadów pobranych w centralnych (rdzenie główne) i marginalnych partiach torfowisk (rdzenie boczne). Ilościowa analiza kierunku i wielkości zmian w składzie zespołów makroszczątkowych np. za pomocą metody PCA (Gałka i in., 2017) nie została podjęta z uwagi na różnice w rozdzielczości próbkowania analizy makroszczątków zarówno w obrębie samych rdzeni głównych (próbkowanie co 2.5 w dolnej oraz co 5 cm w górnej części) jak i rdzeni bocznych (próbkowanie co 5 i 10 cm) oraz z uwagi na mniejszą liczbę gatunków oznaczonych w rdzeniach bocznych, związaną z dużym

stopniem rozkładu osadów organicznych i słabym stopniem zachowania okazów makroszczątków (np. owocki *Betula sect. Albae*).

9. Wyniki

9.1. Wyniki dla głównego celu badawczego 1a – publikacja 1

Wyniki analizy multi-proxy przeprowadzonej dla osadów późnego glacjału i wczesnego holocenu (ok. 13 900–10 000 lat cal BP) torfowisk osuwiskowych Kotoń i Klaklowo w odniesieniu do ich różnych pozycji topograficznych wykazały, że:

- 1) Zidentyfikowane rozbieżności czasowe w zapisie zmian szaty roślinnej (np. etap rozwoju długotrwałego torfowiska niskiego, ekspansja brzozy) w osadach torfowisk Klaklowo i Kotoń wynikają prawdopodobnie z odmiennych lokalnych warunków topograficznych i hydrologicznych obydwu torfowisk (np. kształtu, zasięgu, głębokości i rzeźby zagłębień osuwiskowych, dynamiki zwierciadła wód podziemnych, występowania i liczby cieków wodnych). Z drugiej strony, podobieństwa w zapisie zmian szaty roślinnej w osadach (np. ekspansja lasów sosnowych około 13 650 na Kotoniu i około 13 630 lat cal BP w Klaklowie, recesja Bryopsida około 11 560 na Kotoniu i 11 510 lat cal BP w Klaklowie) są wyraźnie uwarunkowane silnymi i długotrwałymi globalnymi zmianami klimatycznymi (GI-1a-c/allerød, GS-1/młodszy dryas, holocen) i nie wskazują na zależność od wysokości i/lub ekspozycji stanowisk.
- 2) Niemalże równoczesny początek zwiększonej dostawy materiału minerogenicznego do torfowisk Kotoń i Klaklowo, około 11 720 lat cal BP, wskazuje, iż globalne ocieplenie klimatyczne holocenu wywołało podobny i synchroniczny sygnał w zapisie litologicznym obydwu torfowisk, niezależnie od ich położenia topograficznego. Z drugiej strony, charakterystyka zlewni torfowiska, w tym jej powierzchnia, kształt, rzeźba terenu, geologia podłoża skalnego i specyficzne lokalne formy rzeźby terenu, mogą przyczyniać się do znacznie wyraźniejszego zapisu litologicznego słabszych i krótszych oscylacji klimatycznych, w tym przypadku oscylacji GI-1b/Gerzensee i oscylacji preborealnej, co zaobserwowano w przypadku osadów torfowiska Klaklowo. Intensywna sedymentacja materiału minerogenicznego podczas oscylacji preborealnej wymaga jednak dalszego wyjaśnienia ze względu na ograniczoną wiarygodność modelu wiek-głębokość na tej głębokości.

- 3) Na podstawie wyników badań, hipoteza mówiąca, iż zmiany klimatyczne późnego glaciału i wczesnego holocenu zostały zarejestrowane inaczej na torfowisku osuwiskowym Kotoń, charakteryzującym się południową ekspozycją i położeniem blisko grzbietu masywu górskiego, a w inny sposób na torfowisku osuwiskowym Klaklowo, charakteryzującym się północną ekspozycją i położeniem w strefie przydolinnej zbocza, może zostać potwierdzona dla pomniejszych oscylacji klimatycznych, w tym oscylacji GI-1b/Gerzensee i domniemanej oscylacji preborealnej. Ekspansja i/lub zanik dominujących taksonów roślinności (*Pinus*, *Betula sect. Albae*, *Carex*, Bryopsida) oraz dostawa osadu minerogenicznego spowodowana przez globalne zmiany klimatyczne: GI-1a-c/allerød, GS-1/młodszy dryas i holocen, występują w przybliżeniu w tym samym czasie na obydwu torfowiskach osuwiskowych Klaklowo i Kotoń. Wyjątkiem jest późniejsza recesja modrzewia europejskiego (*Larix decidua*), sosny zwyczajnej (*Pinus sylvestris*) i generalnie drzew iglastych (Coniferae) na torfowisku Klaklowo, niż na torfowisku Kotoń, co można przypisać północnej ekspozycji i zróżnicowanej rzeźbie osuwiskowej stanowiska Klaklowo. W ocieplającym się klimacie holocenu, obszar torfowiska mógł pełnić rolę refugium dla niektórych gatunków drzew iglastych (Coniferae) wchodzących w skład lasów borealnych.

9.2. Wyniki dla głównego celu badawczego 1b – publikacje 1, 2 i 3 oraz materiały niepublikowane

Wyniki analizy palinologicznej dla osadów rdzeni bocznych: Klaklowo B1, Klaklowo B2, Kotoń B1 i Kotoń B2 przedstawione są odpowiednio na Figurze 2, 4, 6 i 8, zaś wyniki analizy makroszczątków roślin odpowiednio na Figurze 3, 5, 7 i 9 oraz w Tabeli 2. Etapy paleoekologicznego rozwoju torfowisk Klaklowo i Kotoń wyznaczone w oparciu o analizę rdzeni bocznych, zostały dowiązane do etapów rozwoju zrekonstruowanych w oparciu o analizę osadów rdzeni głównych (Tabela 2, Figura 10 i 11), co umożliwiło określenie, czy wydzielenia przeprowadzone w oparciu o analizę rdzeni bocznych są odmienne niż dla rdzeni głównych. Do porównania sekwencji osadów w rdzeniach głównych i bocznych wykorzystano również daty radiowęglowe (Tabela 1, Figura 10 i 11).

Generalnie, zarówno etapy paleoekologiczne rozwoju torfowiska zrekonstruowane dla profili głównych jak i bocznych charakteryzują się podobnymi zespołami makroszczątków roślin. Dla rdzenia głównego Klaklowa wyróżniono 10 etapów rozwoju paleoekologicznego

zbiornika (wliczając podetapy: KK-3a i KK-3b oraz KK-5a i KK-5b), zaś dla rdzenia bocznego Klaklowo B1 siedem etapów (Figura 10). W wyniku wolniejszego tempa akumulacji lub przerw w sedymentacji i/lub erozji osadów, rdzeń boczny Klaklowo B1 charakteryzował się zredukowaną miąższością sekwencji osadów minerogenicznych: KK-1 wraz z KK-2–KK-3 oraz osadów organicznych KK-4–KK-5 w stosunku do rdzenia głównego. Wydzielenie precyzyjnych granic głębokościowych etapów rozwoju torfowiska w tym przypadku było niemożliwe. Dla rdzenia głównego torfowiska Kotoń wyróżniono 12 etapów rozwoju (wliczając podetapy: KT-1a i KT-1b, KT-4a i KT-4b oraz KT-5a i KT-5b), zaś dla rdzenia bocznego Kotoń B1 wyszczególniono 7 takich etapów (Figura 11). Również w przypadku rdzenia bocznego Kotoń B1 można zaobserwować mocno zredukowaną miąższość sekwencji osadów minerogenicznych: KT1–KT3 w stosunku do rdzenia głównego, uniemożliwiającą dokładniejsze wydzielenie poszczególnych etapów. Dla sekwencji osadów organicznych w przybliżeniu wydzielono etapy KT-4, KT-5a i KT-5b, różnią się one jednak miąższością osadów od analogicznych wydzieleni w rdzeniu głównym (szczególnie etap KT-5a). Niemożliwe było również wydzielenie etapów KT-6–KT-8 w holocenijskiej pokrywie mineralnej rdzenia bocznego. Dodatkowe rdzenie boczne, Klaklowo B2 oraz Kotoń B2, przedstawiają tylko wybrane spągowe fragmenty całości profili, lecz również wykazują dużą zgodność z analogicznymi etapami rozwoju torfowiska wydzielonymi dla rdzeni głównych (Figura 10 i Figura 11). Ponadto, w przypadku rdzenia Klaklowo B2 można zaobserwować wręcz większe miąższości osadów minerogenicznych etapu KK-1–KK-3, co może wskazywać, iż profil ten został nawiercony w najgłębszej części zagłębienia osuwiskowego torfowiska Klaklowo. Niestety brak materiału organicznego umożliwiającego datowanie radiowęglowe metodą AMS poza jedną, prawdopodobnie postarzoną datą z głębokości 260–262,5 cm (15 310–15 055 lat cal BP), uniemożliwia dokładną weryfikację wykonanej korelacji (Tabela 1, Figura 5 i 10).

W przypadku obydwu stanowisk, wyniki wskazują, iż ze względu na reprezentatywność zrekonstruowanych etapów paleoekologicznego rozwoju torfowisk, główne profile osadów nawiercone w centralnej części torfowisk są nie tylko reprezentatywne dla całości zbiornika sedymentacyjnego, ale też pozwalają (w związku z większą miąższością osadów) wydzielić więcej etapów rozwoju torfowiska o wyraźniej sprecyzowanych granicach tych etapów, w stosunku do rdzeni bocznych Klaklowo B1 i Kotoń B1 nawierconych w strefach marginalnych torfowisk. Różnice można zauważyć szczególnie na przykładzie etapów KK-4 i KK-5 rozwoju torfowiska Klaklowo (Figura 10). Podczas gdy w centralnej części zbiornika (rdzeń główny) dochodziło do akumulacji torfów mszystych, w części brzeżnej torf składał się głównie z

korzonków, tkanek, drewniaków i kory roślin naczyniowych, często mocno rozłożonych, a także detrytycznych fragmentów materii organicznej (Tabela 2). Osad organiczny tego rodzaju wskazuje na dużo bardziej zmienne warunki wilgotnościowe i możliwe częste epizody przesuszenia i dostawy do zbiornika allochtonicznej materii organicznej w strefach marginalnych torfowiska. Jest to widoczne również w zapisie palinologicznym rdzenia bocznego Klakłowo B1, w którym występują liczne poziomy pozbawione pyłku (Figura 2, Figura 10). Tak więc analiza rdzeni głównych pozwala na kompletną i bardziej szczegółową rekonstrukcję historii rozwoju torfowisk, zaś hipoteza robocza „Analiza makroszczałków przeprowadzona jedynie w obrębie jednego profilu może nie być reprezentatywna dla całego zbiornika sedymentacyjnego” pozostaje w przypadku analizowanych danych niepotwierdzona.

9.3. Wyniki dla głównego celu badawczego 1c – publikacje 2 i 3

W celu określenia zmian roślinności w trakcie krótkotrwałego ochłodzenia starszego dryasu (100–200 lat), zrekonstruowano etapy lokalnego rozwoju paleoekologicznego torfowisk osuwiskowych Klakłowo i Kotoń podczas faz klimatycznych bølling-starszy dryas-allerød i skorelowano je z dostępnymi chronologiami absolutnymi (Ammann i in., 2013; Litt i in., 2001; Rasmussen i in., 2014). Następnie zaś prześledzono czy i w jaki sposób krótkotrwała oscylacja klimatyczna GI-1d /starszy dryas (14 025–13 904 lat BP) (Rasmussen i in., 2014) wpłynęła na lokalny i regionalny zapis paleo-środowiska i zmian szaty roślinnej w obydwu stanowiskach.

9.3.1. Rekonstrukcja etapów rozwoju torfowisk i korelacja z ponadregionalnymi chronologiami absolutnymi

Rozwój paleo-zbiorników wodnych/torfowisk Klakłowo i Kotoń w okresie bølling-starszy dryas-allerød (ok. 14 600–13 500 lat cal BP) przebiegał wieloetapowo. W sekwencji osadów torfowiska Klakłowo wyróżniono cztery etapy paleoekologiczne: zbiornik wodny I w otoczeniu prawdopodobnie otwartej przestrzeni (spowodowanej lokalnymi warunkami nowo powstałych osuwisk i/lub chłodnym klimatem) (KK-1), krótkotrwałe torfowisko otoczone stepo-tundrą (KK-2), zbiornik wodny II otoczony lasem borealnym zdominowanym przez brzozę (*Betula*) (etap podzielony na dwa podetapy KK-3a i KK-3b) oraz długotrwałe torfowisko otoczone lasem borealnym zdominowanym przez sosnę (*Pinus*) (KK-4). W

sekwencji osadów torfowiska Kotoń wyróżniono cztery paleoekologiczne stadia rozwoju: zbiornik wodny ubogi w roślinność przypuszczalnie w otwartym otoczeniu (KT-1), zbiornik wodny z sukcesją roślin wodnych prawdopodobnie otoczony siedliskami stepowo-tundrowymi (KT-2), torfowisko niskie wybitnie zasobne w węglany (KT-3) otoczone (zarastającą?) stepotundrą i torfowisko średnio zasobne w węglany w otoczeniu borealnego lasu brzoźowo-sosnowego (KT-4).

Porównując radiowęglowe chronologie absolutne uzyskane dla stanowisk Klakłowo i Kotoń z różnymi chronologiami ponadregionalnymi, późnoglacialna sekwencja torfowiska Klakłowo może być skorelowana z zapisem rdzeni lodowych Grenlandii (Rasmussen i in., 2014) i osadami jeziora Gerzensee w Szwajcarii (Ammann i in., 2013) w większym stopniu niż z zapisem późnego glaciału w osadach jeziora Meerfelder Maar w regionie Eifel w Niemczech (Litt i in., 2001). Zgodnie z chronologiami NGRIP i Gerzensee, w sekwencji osadów torfowiska Klakłowo etap KK-1 odpowiada ochłodzeniu GS-2/najstarszy dryas i ociepleniu klimatu GI-1e/bølling, etap KK-2 ochłodzeniu GI-1d/starszy dryas, zaś etapy KK-3a, KK-3b i KK-4 odpowiadają ociepleniu GI-1c/allerød. W sekwencji osadów torfowiska Kotoń, etap KT-1 odpowiada ociepleniu GI-1e/bølling i prawdopodobnie także poprzedzającemu go ochłodzeniu GS-2/najstarszy dryas, etap KT-2 odpowiada ochłodzeniu GI-1d/starszy dryas, KT-3 prawdopodobnie okresowi przejściowemu pomiędzy GI-1d/starszy dryas i GI-1c/allerød, zaś KT-4 odpowiada ociepleniu GI-1c/allerød.

9.3.2. Charakterystyka szaty roślinnej

W sekwencji osadowej stanowiska Kotoń, ochłodzenie klimatu GI-1d/starszy dryas odpowiada etapowi KT-2 paleoekologicznego rozwoju tego torfowiska, którego zakres czasowy został oszacowany na od ok. $14\ 070 \pm 72$ do ok. $13\ 900 \pm 56$ lat cal BP (ok. 170 lat). W trakcie tego etapu powstawały osady o charakterze gytii zakumulowanej w oligo- do mezotroficznym zbiorniku wodnym z roślinnością zdominowaną przez łąki ramienicowe (Characeae) i inne gatunki makrofitów (*Potamogeton alpinus*, *Batrachium* sp.) oraz mchy brunatne (Bryopsida) reprezentowane przez arktyczno-borealny gatunek *Sarmentypnum trichophyllum* i turzyce (*Carex nigra*, *Carex diandra*, *Carex rostrata* i *Carex magellanica*). Zbiornik ten był prawdopodobnie otoczony siedliskami stepowo-tundrowymi, udokumentowanymi przez makroszczałki *Dryas octopetala* i *Androsace* cf. *chamaejasme*.

W sekwencji osadowej stanowiska Klakłowo, ochłodzenie klimatu GI-1d/starszy dryas odpowiada etapowi KK-2 paleoekologicznego rozwoju tego torfowiska, którego zakres czasowy został oszacowany na okres od ok. 14 040 ± 61 do ok. 13 900 ± 56 lat cal BP (ok. 170 lat). Etap ten dokumentują osady minerogeniczno-organiczne zdeponowane w krótkotrwałym okresie rozwoju torfowisku, które powstało prawdopodobnie w wyniku wypłyenia wcześniej istniejącego paleo-jeziora. Dominująca obecność taksonów roślin torfowiskowych: *Valeriana simplicifolia/dioica*, *Carex rostrata*, *Carex diandra*, *Eleocharis palustris* i *Phragmites australis* wskazuje na wahania poziomu wody wynoszące ok. 1 m w skali roku (Gaillard i Birks, 2007). Makroszczałki roślinne należące do *Dryas octopetala*, *Poa* cf. *alpina* i *Androsace* cf. *chamaejasme*, redeponowane do basenu sedymentacyjnego sugerują występowanie stepo-tundry w otoczeniu zbiornika, typowej dla zimnych i suchych warunków klimatycznych.

9.3.3. Podobieństwa w zapisie zmian szaty roślinnej pomiędzy stanowiskami

Generalnie, oscylacja klimatyczna starszego dryasu była związana z nawrotem zimnego i suchego klimatu kontynentalnego, typowego dla późnego glacjału. W sekwencjach osadowych zarówno Kotoń jak i Klakłowo, w okresie odpowiednio KT-2 i KK-2, zespoły makroszczałkow roślin wskazują na arktyczne/alpejskie warunki klimatyczne wokół tych stanowisk tj. występowanie tam stepo-tundry. W przypadku lokalnych zmian roślinności i paleohydrologicznych, oscylacja klimatyczna GI-1d/starszego dryasu została zarejestrowana podobnie w obydwu stanowiskach jako spłylenie istniejących paleo-zbiorników wodnych. Podobny zapis spływania zbiorników podczas GI-1d/starszego dryasu można odnaleźć w innych stanowiskach w Europie (Bos i in., 2013, 2017; Feurdean i Bennike, 2004), w których to przypadkach proces ten przypisywano oddziaływaniu suchych warunków klimatycznych. Niemniej jednak, w przypadku stanowisk Kotoń i Klakłowo konieczne są bardziej szczegółowe badania multi-proxy, aby odróżnić wpływ zmian klimatu od sukcesji autogenicznej. Dlatego też w identyfikowaniu etapów KT-2 i KK-2 bezpośrednio z ochłodzeniem starszego dryasu należy zachować pewną ostrożność (Rasmussen i in., 2014).

9.3.4. Porównanie z chronozonami wyznaczonymi we wcześniejszych badaniach

Dzięki zastosowaniu datowania radiowęglowego AMS i analizy makroszczątków roślin o wysokiej rozdzielczości, została doprecyzowana rzeczywista miąższość osadów deponowanych w starszym dryasie (obecnie tożsamym z GI-1d), która we wcześniejszych badaniach torfowisk Kotoń i Klakłowo została oszacowana na ok. 0,5 m (Margielewski, 2001a, 2001b; Margielewski i in., 2003). Co więcej, w profilu Klakłowo w przedziale głębokości zidentyfikowanym palinologicznie jako osady starszego dryasu w poprzednich badaniach (Margielewski, 2001a), w bieżących wynikach makroszczątkowych zaobserwowano rozwój sukcesji roślin wodnych (zdominowanych przez Characeae), która wraz z sukcesją lasu borealnego w zlewni zbiornika wodnego, sygnalizuje ocieplenie GI-1c3/allerød. Analogiczne zmiany roślinności zaobserwowano również w nowych danych pyłkowych, co sugeruje, że faza klimatyczna allerødu nastąpiła wcześniej niż ustalono to na podstawie poprzedniej analizy palinologicznej (Margielewski, 2001a).

W przypadku różnic w zakresie czasowym pomiędzy wcześniej określonymi chronozonami pyłkowymi dla stanowiska Klakłowo i Kotoń (Margielewski i in., 2003) a stratygrafią rdzeni lodowych Grenlandii (Rasmussen i in., 2014), należy podkreślić, że ochłodzenie klimatu GI-1d/starszy dryas jest wyraźnie zdefiniowane pod względem zakresu czasowego (14 025–13 904 lat BP), podczas gdy w przypadku wielu stanowisk (w tym stanowiska Kotoń i Klakłowo) ochłodzenie klimatu starszego dryasu zostało rozpoznane jako oparte wyłącznie o diagramy pyłkowe, bez odniesienia do konkretnych granic czasowych zdefiniowanych w chronologiach ponadregionalnych (Björck i in., 1998; Mangerud i in., 1974; Rasmussen i in., 2014). W związku z tym możliwe są rozbieżności w zakresie głębokości pomiędzy podziałami sekwencji osadów (granicami chronozon) opartymi na danych palinologicznych i podziałami opartymi na chronologii absolutnej.

Zweryfikowanie zasięgu granic chronozony starszego dryasu wydzielonych na podstawie archiwalnych diagramów pyłkowych, z wykorzystaniem bieżących danych palinologicznych, jest utrudnione z uwagi na poziomy płonny pod względem obecności ziaren pyłku w spągowych, minerogenicznych partiach profili obydwu stanowisk (niemożność wydzielenia LPAZ). Częste wahania poziomu wody i możliwe okresowe wysychanie zbiorników, charakterystyczne dla zbiorników wodnych i torfowisk powstałych w zagłębieniach osuwiskowych, oraz wynikające z nich zmiany warunków natlenienia (na co wskazują dane geochemiczne) były prawdopodobnie jedną z głównych przyczyn degradacji pyłku podczas najwcześniejszego etapu rozwoju zbiorników wodnych Klakłowa i Kotonia.

Należy również uwzględnić inne możliwe procesy pre-, syn- i postdepozycyjne powodujące degradację pyłku. Kwestia nieciągłego zapisu pyłkowego wymaga jednak dalszych badań.

9.4. Wyniki dla drugorzędnego celu badawczego 2a – publikacje 1, 2 i 3 oraz materiały niepublikowane

Kotoń – rdzeń główny. We wcześniejszej analizie palinologicznej późnoglacialnych osadów z torfowiska Kotoń na głębokości ok. 450–400 cm zarejestrowano występowanie pyłku roślin ciepłolubnych: *Corylus avellana*, *Ulmus*, *Tilia* undiff., *Quercus*, *Carpinus betulus* oraz pyłku *Fagus sylvatica* i *Abies alba* o udziałach procentowych około lub poniżej 1% (Margielewski, 2001b; Margielewski i in., 2003). Jak pokazują wyniki analizy makroszczątków roślin dla rdzenia głównego torfowiska Kotoń, ten interwał głębokości jest bardzo ubogi w makroszczałki (jedynie sporadyczne znaleziska *Juncus*, *Alchemilla* sp., *Carex rostrata*, *Scirpus sylvaticus*, *Bryopsida*, Characeae i innych organizmów wodnych). Jest to również poziom występowania osadów pylastych z istotną zawartością frakcji piaszczystej i czasami również drobnych fragmentów gruzu skalnego. Występowania makroszczałków ciepłolubnych taksonów drzew oraz buka i jodły nie stwierdzono.

Klakłowo – rdzeń główny. Dla podobnego odcinka czasowego, w osadach stanowiska Klakłowo (głębokość ok. 340–280 cm) podczas wcześniejszych badań zarejestrowano jedynie śladowe ilości pyłku ciepłolubnego *Corylus* (Margielewski, 2001a). Analiza palinologiczna wykonana w ramach niniejszego projektu dała nieco inne rezultaty w postaci prawie ciągłego zapisu pyłku *Corylus avellana* na całej długości rdzenia głównego osadów torfowiska Klakłowo (ok. 332,5–0 cm; w interwale ok. 367–332,5 cm występuje zupełny brak pyłku) i bardziej zmiennej zawartości pyłku *Quercus* w sekwencjach późnoglacialnych. Warto jednak zauważyć, że w najgłębszych partiach profilu osadów, gdzie stwierdzono występowanie pyłku tych taksonów (332,5–287,5 cm), towarzyszy im również duży udział pyłku skorodowanego, który jest charakterystyczny dla utworów redeponowanych. Analiza makroszczałków roślin w osadach rdzenia głównego torfowiska Klakłowo dla wspomnianych późnoglacialnych sekwencji, w których występował pyłek leszczyny i dębu, nie wykazała występowania nasion, owoców lub części wegetatywnych tych taksonów.

Kotoń – rdzenie boczne. W osadach spągowych rdzenia bocznego Kotoń B1 nie stwierdzono obecności pyłku roślin klimatu umiarkowanego. Pojawia się on dopiero w części

holoceńskiej profilu (LPAZ KT_B1-4 i KT_B1-5) (Figura 6). Również wyniki analizy makroszczątków roślin przeprowadzone dla tego rdzenia, nie wykazały obecności nasion, owoców lub części wegetatywnych taksonów roślin ciepłolubnych (Figura 7).

W przypadku dodatkowego rdzenia bocznego Kotoń B2, pyłek drzew klimatu umiarkowanego (*Corylus*, *Fraxinus*, *Quercus*, *Ulmus*) występuje w spągowej części profilu (LPAZ KT_B2-1a), w której ogólna zawartość pyłku jest bardzo niska (Figura 8). Sumaryczny udział gatunków typowych dla klimatu umiarkowanego osiąga maksymalnie 12% w najniższej próbce (400 cm). Wyniku tego nie można jednak interpretować jako dowodu na ocieplenie klimatu bądź istnienie refugium roślin ciepłolubnych u schyłku ostatniego glacjału w tym rejonie. W materiale stwierdzono obecność zarówno ziaren pyłku jak i spor pochodzących ze starszych prawdopodobnie neogeńskich osadów. Obecne były także cysty morskich glonów Dinoflagellata (dinocysty). Spektra pyłkowe są więc silnie zanieczyszczone materiałem starszym, co może świadczyć o jego redepozycji. Również słaby stan zachowania ziaren pyłku może wskazywać na ich redepozycję, ale także może być efektem przesychania osadu i działania warunków tlenowych. Wysoki udział NAP wskazuje na dominację roślin zielnych w lokalnej roślinności, co sugeruje surowy klimat, niesprzyjający przetrwaniu, a tym bardziej rozmnażaniu się gatunków o wyższych wymaganiach termicznych. Co więcej, LPAZ KT_B2-1a pokrywa się z występowaniem w profilu piaszczystych osadów pylastych prawie zupełnie pozbawionym makroszczątków roślin (Figura 9).

Klakłowo – rdzenie boczne. W przypadku rdzenia bocznego Klakłowo B1, pyłek roślin ciepłolubnych (*Corylus*, *Ulmus* i *Quercus*) został stwierdzony w spągowej części profilu (LPAZ KK_B1-1) (Figura 2). Próbki pobrane z głębokości 250 i 255 cm wykazują zaskakująco wysoką frekwencję palinomorfe oraz znaczny (do 30%) udział pyłku roślin klimatu umiarkowanego. Pyłek ten jest dobrze zachowany i nie nosi śladów redepozycji, a w osadach nie zaobserwowano innych jej wskaźników. Pomimo tego wydaje się, że pyłek nie pochodzi bezpośrednio z analizowanego osadu, lecz mógł zostać przemieszczony z wyższych partii profilu (LPAZ KK_B1-6 i KK_B1-7) w trakcie pobierania próbek. Wskazuje na to duże podobieństwo spektrum pyłkowych, w tym obecność taksonów *Ulmus* i *Tilia* na zbliżonym poziomie udziałów procentowych. Tak bogate i dobrze zachowane spektrum pyłkowe nie mogłoby zachować się w osadach piaszczystych. Ostateczne potwierdzenie pochodzenia pyłku wymaga jednak uzyskania wyników datowania radiowęglowego. Niestety brak materiału organicznego w spągowej części profilu uniemożliwia wykonanie takiego datowania. Jedyna data radiowęglowa została pozyskana dla próbki z głębokości 235–237,5 cm, wynosi 14 157–

13 879 lat cal BP i może sugerować jednak pochodzenie pyłku ze starszych utworów. Próbki 250 i 255 cm są osadem pylastym z dodatkiem frakcji piaszczystej i drobnych fragmentów skał. Jest to utwór ubogi w makroszczałki (pojedyncze znaleziska *Carex rostrata*, *Scirpus sylvaticus* i *Cenococcum geophilum*) (Figura 3). Występowania tu makroszczałków taksonów roślin termofilnych jednak nie stwierdzono.

W przypadku dodatkowego rdzenia bocznego Klaklowo B2, analiza palinologiczna wykazała obecność nielicznych ziaren pyłku (<2%) drzew klimatu umiarkowanego: *Corylus*, *Quercus*, *Tilia* i *Carpinus* (LPAZ KK_B2-2), przy maksymalnym sumarycznym udziale pyłku wynoszącym 10% (Figura 4). Stwierdzono również występowanie pyłku *Abies* i *Fagus sylvatica*. Obecność pyłku taksonów ciepłolubnych należy interpretować jako rezultat redepozycji starszego materiału, najprawdopodobniej pochodzenia neogeńskiego. Świadczy o tym występowanie pyłku taksonów termofilnych, takich jak *Nyssa* i *Eucommia*, które na obszarze współczesnej Polski przetrwały jedynie do wczesnego plejstocenu (Birkenmajer i Stuchlik, 1975; Stuchlik, 1994; Winter, 2015). W materiale dominują palinomorfy silnie skorodowane, a ponadto licznie występują dinocysty. Zaobserwowano również wskaźniki spływu powierzchniowego – liczne strzępki grzybni oraz zarodniki *Glomus*. Spektrum pyłkowe cechuje wysoki udział NAP z dominacją pyłku roślin zielnych typowych dla lokalnego środowiska, co wskazuje na chłodny klimat. Takie spektrum palinologiczne nie potwierdza istnienia warunków sprzyjających rozwojowi refugium roślin ciepłolubnych w późnym glacie w badanym rejonie. LPAZ KK_B2-2 został wyznaczony w obrębie osadów pylastych zawierających pojedyncze makroszczałki *Carex* sp., Bryopsida, *Potamogeton alpinus*, stopniowo wzrastającą liczbę oospor Characeae i pewną liczbę makroszczałków m.in. Ostracoda, *Daphnia* sp. i Porifera (Figura 5). Nie stwierdzono jednak wśród nich makroszczałków buka, jodły i ciepłolubnych taksonów drzew, co potwierdza prawdopodobną redepozycję pyłku tych roślin do basenu torfowiska.

Podsumowując, analizy palinologiczne przeprowadzone dla późnoglacialnych osadów torfowisk Kotoń i Klaklowo dały wyniki potwierdzające jedno z rozważanych wcześniej wyjaśnień, iż pyłek roślin termofilnych jest redeponowany (Margielewski i in., 2003). Jedynie w przypadku rdzenia bocznego Klaklowo B1 znaleziono pyłek *Corylus*, *Ulmus* i *Quercus* nie wykazujący ewidentnych śladów redepozycji. Jednakże, ani w przypadku tego profilu osadów ani też żadnego z pozostałych, w zapisie makroszczałków roślin nie stwierdzono obecności nasion, owoców lub części wegetatywnych wskazujących na lokalne występowanie ciepłolubnych taksonów drzew: *Corylus*, *Ulmus*, *Quercus*, *Tilia*, *Carpinus betulus* oraz

gatunków *Abies alba* i *Fagus sylvatica*. Dlatego też hipoteza dotycząca występowania na stanowisku Kotoń (jak również na stanowisku Klaklowo) refugiów roślin termofilnych w późnym glacie nie może być potwierdzona na podstawie bieżących wyników badań.

9.5. Wyniki dla drugorzędного celu badawczego 2b – materiały niepublikowane

Na podstawie rozkładu wieku modelowanego ^{14}C dla późnoglacialnych sekwencji osadów torfowisk Kotoń i Klaklowo, wytypowano przedziały głębokości (interwały) osadów, w których z dużym prawdopodobieństwem można było spodziewać się występowania poziomów tefry, pochodzącej z erupcji wulkanów europejskich w późnym glacie (Campi Flegrei we Włoszech i Laacher See w Niemczech). Z tych horyzontów pobrano więc próbki osadów do analizy tefry. W efekcie, otrzymano następujące wyniki:

1) Neapolitan Yellow Tuff (NYT) (erupcja wulkanu Campi Flegrei datowana na 14 588–13 884 lat cal BP)

W torfowisku osuwiskowym Klaklowo, w osadach występujących w przedziale głębokości 330–342,5 cm (w tym odcinku „pilotażowym”, próbki pobierano co 0,5 cm) stwierdzono występowanie sporadycznych ziaren o wielkości 100–300 μm posiadających niektóre cechy tefry: ostre, nieobtoczone krawędzie ziaren (Figura 12 A i D), pęcherzyki gazu występujące w ziarnach (Figura 12 B) oraz ziarna prążkowanie (Figura 12 C).

Ponadto, w torfowisku osuwiskowym Klaklowo, w przedziale głębokości 309–359 cm (próbki pobierano co 10 cm) stwierdzono występowanie licznych ziaren prawdopodobnie stanowiących tefrę NYT. W torfowisku osuwiskowym Kotoń, w przedziale głębokości 363–495 cm (próbki co 10 cm) również stwierdzono występowanie licznych ziaren szkliwa wulkanicznego: datowania bezwzględne osadów w których występowała tefra wskazują, że prawdopodobnie jest ona tefrą z poziomu NYT.

1) Laacher See Tephra (LST) (erupcja wulkanu Laacher See datowana na 12 979–12 889 lat cal BP)

Podobnie jak dla tefry typowej dla NYT, w torfowisku osuwiskowym Klaklowo, w osadach z przedziału głębokości 190–201 cm (próbki pobierano co 1 cm) stwierdzono występowanie licznych szklistych ziaren izotropowej krzemionki, prawdopodobnie stanowiących tefrę LST. W torfowisku osuwiskowym Kotoń, w przedziale głębokości 248–254

cm (próbki pobierano co 1 cm) również stwierdzono występowanie licznych szklistych ziaren charakteryzujących się izotropowością, prawdopodobnie także stanowiących tefrę LST.

Ponieważ tło skalne w większości analizowanych próbek osadu charakteryzuje się bardzo dużą liczbą ziaren o charakterze szkliwa wulkanicznego (Figura 12 E i F), konieczne jest wykonanie dalszych, dokładniejszych badań, tj. zdjęć i analizy geochemicznej za pomocą mikroskopu skaningowego (SEM), które pozwolą jednoznacznie stwierdzić, czy znalezione ziarna są w rzeczywistości pochodzenia wulkanicznego i czy pod względem składu geochemicznego są zgodne z pyłami wulkanicznymi NYT i LST.

10. Wnioski i podsumowanie

W badaniach wykazano, że (z pewnymi odstępstwami) ekspansja i/lub zanik dominujących taksonów roślin (*Pinus*, *Betula* sect. *Albae*, *Carex*, Bryopsida) oraz zmiany w dostawie materii minerogenicznej spowodowane globalnymi zmianami klimatycznymi (wg chronologii absolutnej rdzeni Grenlandii): ociepleniem alleroðu (GI-1a-c, 13 904–12 846 lat BP), ochłodzeniem młodszego dryasu (GS-1, 12 846–11 653 lat BP) i ociepleniem holoceni (ok. <11 653 lat BP), następowały w przybliżeniu w tym samym czasie na torfowiskach osuwiskowych Klaklowo i Kotoń i nie były uwarunkowane ekspozycją i/lub wysokością położenia torfowisk. Z drugiej strony, w czasie trwania krótszych oscylacji klimatycznych, ochłodzenia Gerzensee (GI-1b, 13 261–13 049 lat BP) i chłodnej oscylacji preborealnej (ok. 11 400–11 100 lat cal BP), zaobserwowano znacznie wyraźniejszy zapis litologiczny (wzmóŜona dostawa materiału minerogenicznego) w obrębie torfowiska Klaklowo, niŜ w przypadku sekwencji osadowej stanowiska Kotoń, co mogło wynikać z charakterystyki zlewni torfowiska Klaklowo, w tym jej powierzchni, kształtu, morfologii stoku, geologii podłóŜa skalnego i specyficznych lokalnych form rzeźby terenu (**publikacja 1**).

W przypadku obydwu stanowisk, stwierdzono, iŜ główny profile osadów pobrane w centralnej części torfowisk sã nie tylko reprezentatywne dla całego zbiornika sedymentacyjnego, ale teŜ pozwalajã (w zwiãzku z wiêkszã miãgŝoŝciã osadu) odtworzyç wiêcej etapów rozwoju torfowiska o wyraźniej sprecyzowanych granicach tych etapów w stosunku do rdzeni bocznych Klaklowo B1 i Kotoń B1 nawierconych w strefach marginalnych torfowisk (**publikacje 1, 2 i 3 oraz materiały niepublikowane**).

Oscylacja klimatyczna starszego dryasu (GI-1d, 14 025–13 904 lat BP), związana z oddziaływaniem zimnego i suchego klimatu kontynentalnego, w sekwencjach osadowych zarówno Kotoń jak i Klakłowa reprezentowana jest przez zespoły makroszczałków roślin, wskazujące na występowanie stepo-tundry i panowanie arktyczno/alpejskich warunków klimatycznych. W przypadku lokalnych zmian roślinności i paleohydrologicznych, oscylacja klimatyczna GI-1d/starszego dryasu została zarejestrowana podobnie w obydwu stanowiskach, jako wypływanie istniejących paleo-zbiorników wodnych (**publikacje 2 i 3**).

W oparciu o wyniki analiz palinologicznych wykonanych dla profili głównych i bocznych wykazano, iż pyłek roślin termofilnych (*Corylus*, *Ulmus*, *Quercus*, *Tilia*, *Carpinus betulus*) w późnoglacialnych sekwencjach osadów torfowisk Kotoń i Klakłowo jest redeponowany ze starszych pokryw stokowych. Również w zapisie makroszczałków roślin nie stwierdzono obecności nasion, owoców lub części wegetatywnych roślin, wskazujących na lokalne występowanie tych taksonów. Hipoteza o występowaniu refugium roślin ciepłolubnych na stanowisku Kotoń w późnym glacie nie została zatem potwierdzona bieżącymi wynikami badań (**publikacje 1, 2 i 3 oraz materiały niepublikowane**).

W przedziałach głębokości wytypowanych (na podstawie wieku modelowanego) do analizy potencjalnych horyzontów tefry Neapolitan Yellow Tuff (NYT) (14 588–13 884 lat cal BP) oraz Laacher See Tephra (LST) (12 979–12 889 lat cal BP), zarówno w przypadku stanowiska Klakłowo jak i Kotoń stwierdzono występowanie licznych ziaren posiadających cechy tefry, jednakże konieczne jest przeprowadzenie szczegółowych analiz geochemicznych, aby potwierdzić ich pochodzenie z poszczególnych erupcji: NYT i LST (**materiały niepublikowane**).

Podsumowując, wykazano, iż torfowiska osuwiskowe Kotoń i Klakłowo stanowią unikatowe stanowiska osadów późnego glaciału i holocenu w skali nie tylko Karpat zachodnich i Polski, ale również w skali Europy. Wyniki przeprowadzonych badań wnoszą znaczący wkład w stan wiedzy o lokalnych i regionalnych zmianach szaty roślinnej, chronostratygrafii i klimatostratygrafii późnego glaciału oraz dają solidne podstawy do dalszych, rozszerzonych i bardziej szczegółowych badań typu multi-proxy osadów tych torfowisk, jak również podstawy metodyczne do analiz osadów z innych stanowisk późnoglacialnych w Karpatach zachodnich.

11. Literatura

- Aalto, M., 1970. Potamogetonaceae fruits I. Recent and subfossil endocarps of the Fennoscandian species. *Acta Bot. Fenn.* 88, 1–85.
- Alexandrowicz, Z., Margielewski, W., 2010. Impact of mass movements on geo- and biodiversity in the Polish Outer (Flysch) Carpathians. *Geomorphology* 123, 290–304. <https://doi.org/10.1016/j.geomorph.2010.07.020>
- Ammann, B., Birks, H., Brooks, S.J., Eicher, U., Lemdahl, G., Schwander, J., Wick, L., Wright, H.E., 2000. Biotic responses to rapid climatic changes - an attempt to a synthesis. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 159, 313–347.
- Ammann, B., Van Leeuwen, J.F.N., Van der Knaap, W.O., Lischke, H., Heiri, O., Tinner, W., 2013. Vegetation responses to rapid warming and to minor climatic fluctuations during the Late-Glacial Interstadial (GI-1) at Gerzensee (Switzerland). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 391, 40–59. <https://doi.org/10.1016/j.palaeo.2012.07.010>
- Anderberg, A.-L., 1994. Atlas of seeds and small fruits of Northwest-European plant species with morphological descriptions. Part 4. Resedaceae–Umbelliferae. Swedish Museum of Natural History, Stockholm.
- Bank Danych o Lasach, 2025. <https://www.bdl.lasy.gov.pl/portal/mapy> (dostęp 03.05.2025).
- Baumgart-Kotarba, M., Kotarba, A., 1993. Późnoglacialne i holocenijskie osady z Czarnego Stawu Gąsienicowego w Tatrach, w: Kotarba, A. (Red.), *Dokumentacja Geograficzna. Z Badań Fizyczno-Geograficznych w Tatrach*. Instytut Geografii i Przestrzennego Zagospodarowania PAN, Warszawa, pp. 9–30.
- Bennett, K.D., 1996. Determination of the number of zones in a biostratigraphical sequence. *New Phytol.* 132, 155–170.
- Berggren, G., 1969. Atlas of seeds and small fruits of Northwest-European plant species with morphological descriptions. Part 2: Cyperaceae. Swedish Natural Science Research Council, Stockholm.
- Berggren, G., 1981. Atlas of seeds and small fruits of Northwest-European plant species with morphological descriptions. Part 3: Salicaceae - Cruciferae. Swedish Museum of Natural History, Stockholm.
- Berglund, B.E., Ralska-Jasiewiczowa, M., 1986. Pollen Analysis and Pollen Diagrams, w: Berglund, B., Ralska-Jasiewiczowa, M. (Red.), *Handbook of Holocene Palaeoecology and Palaeohydrology*. John Wiley & Sons, Chichester–New York, pp. 455–484.
- Beug, H.J., 2004. Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete. Verlag Dr. Friedrich Pfeil, München.
- Birkenmajer, K., Stuchlik, L., 1975. Early Pleistocene pollen-bearing sediments at Szaflary, West Carpathians, Poland. *Acta Palaeobot.* 16, 1–19.
- Birks, H.H., 2003. The importance of plant macrofossils in the reconstruction of Lateglacial vegetation and climate: Examples from Scotland, western Norway, and Minnesota, USA. *Quat. Sci. Rev.* 22, 453–473. [https://doi.org/10.1016/S0277-3791\(02\)00248-2](https://doi.org/10.1016/S0277-3791(02)00248-2)
- Birks, H.H., 2013. Plant macrofossil introduction, w: Elias, S.A., Mock, C.J. (Red.),

- Encyclopedia of Quaternary Science. Elsevier, Amsterdam, pp. 593–612. <https://doi.org/https://doi.org/10.1016/B978-0-444-53643-3.00203-X>
- Birks, H.J.B., Willis, K.J., 2008. Alpines, trees, and refugia in Europe. *Plant Ecol. Divers.* 1, 147–160. <https://doi.org/10.1080/17550870802349146>
- Björck, S., Walker, M.J.C., Cwynar, L.C., Johnsen, S.J., Knudsen, K.-L., Lowe, J.J., Wohlfarth, B., 1998. An event stratigraphy for the Last Termination in the North Atlantic region based on the Greenland ice-core record: a proposal by the INTIMATE group. *J. Quat. Sci.* 13, 283–292. [https://doi.org/https://doi.org/10.1002/\(SICI\)1099-1417\(199807/08\)13:4<283::AID-JQS386>3.0.CO;2-A](https://doi.org/https://doi.org/10.1002/(SICI)1099-1417(199807/08)13:4<283::AID-JQS386>3.0.CO;2-A)
- Blockley, S.P.E., Pyne-O'Donnell, S.D.F., Lowe, J.J., Matthews, I.P., Stone, A., Pollard, A.M., Turney, C.S.M., Molyneux, E.G., 2005. A new and less destructive laboratory procedure for the physical separation of distal glass tephra shards from sediments. *Quat. Sci. Rev.* 24, 1952–1960. <https://doi.org/10.1016/j.quascirev.2004.12.008>
- Blott, S.J., Pye, K., 2001. Technical communication GRADISTAT: A grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surf. Process. Landforms* 26, 1237–1248.
- Bos, J.A.A., De Smedt, P., Demiddele, H., Hoek, W.Z., Langohr, R., Marcelino, V., Van Asch, N., Van Damme, D., Van der Meeren, T., Verniers, J., Boeckx, P., Boudin, M., Court-Picon, M., Finke, P., Gelorini, V., Gobert, S., Heiri, O., Martens, K., Mostaert, F., Serbruyns, L., Van Strydonck, M., Crombé, P., 2017. Multiple oscillations during the Lateglacial as recorded in a multi-proxy, high-resolution record of the Moervaart palaeolake (NW Belgium). *Quat. Sci. Rev.* 162, 26–41. <https://doi.org/10.1016/j.quascirev.2017.02.005>
- Bos, J.A.A., Verbruggen, F., Engels, S., Crombé, P., 2013. The influence of environmental changes on local and regional vegetation patterns at Rieme (NW Belgium): Implications for Final Palaeolithic habitation. *Veg. Hist. Archaeobot.* 22, 17–38. <https://doi.org/10.1007/s00334-012-0356-0>
- Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. *Radiocarbon* 51, 337–360. <https://doi.org/10.1017/s0033822200033865>
- Bronk Ramsey, C., 2021. Oxcal version 4.4.4. <https://c14.arch.ox.ac.uk> (dostęp 13.11.2022).
- Bronk Ramsey, C., Albert, P.G., Blockley, S.P.E., Hardiman, M., Housley, R.A., Lane, C.S., Lee, S., Matthews, I.P., Smith, V.C., Lowe, J.J., 2015. Improved age estimates for key Late Quaternary European tephra horizons in the RESET lattice. *Quat. Sci. Rev.* 118, 18–32. <https://doi.org/10.1016/j.quascirev.2014.11.007>
- Cappers, R.T.J., Bekker, R.M., Jans, J.E.A., 2012. Digital seed atlas of the Netherlands/ Digitale Zadenatlas van Nederland, 2nd ed. Barkhuis Publishing & Groningen University Library, Groningen.
- Climate Data, 2024. Stróża i Zawadka. <https://pl.climate-data.org/europa/polska/lesser-poland-voivodeship/stroza-450713/>, <https://pl.climate-data.org/europa/polska/lesser-poland-voivodeship/zawadka-450812/> (dostęp 08.08.2024).
- David, F., 1993. Altitudinal variation in the response of the vegetation to Late-glacial climatic events in the northern French Alps. *New Phytol.* 125, 203–220.
- De Klerk, P., 2004. Confusing concepts in Lateglacial stratigraphy and geochronology: Origin,

- consequences, conclusions (with special emphasis on the type locality Bøllingsø). *Rev. Palaeobot. Palynol.* 129, 265–298. <https://doi.org/10.1016/j.revpalbo.2004.02.006>
- Dzieduszyńska, D.A., Forsytek, J., 2019. Chronostratigraphy of the Late Vistulian in Central Poland and the correlation with Vistulian glacial phases. *Stud. Quat.* 36, 137–145. <https://doi.org/10.24425/sq.2019.126385>
- Erdtman, G., 1943. An introduction to pollen analysis. *Chronica Botanica*, Waltham, Massachusetts.
- Erdtman, G., 1960. The acetolysis method. *Sven. Bot. Tidskr.* 54, 561–564.
- Fægri, K., Iversen, J., 1989. Textbook of pollen analysis, 4th ed. John Wiley & Sons, Chichester.
- Feurdean, A., Bennike, O., 2004. Late Quaternary palaeoecological and palaeoclimatological reconstruction in the Gutaiului Mountains, northwest Romania. *J. Quat. Sci.* 19, 809–827. <https://doi.org/10.1002/jqs.872>
- Feurdean, A., Gałka, M., Tanțău, I., Geantă, A., Hutchinson, S.M., Hickler, T., 2016. Tree and timberline shifts in the northern Romanian Carpathians during the Holocene and the responses to environmental changes. *Quat. Sci. Rev.* 134, 100–113. <https://doi.org/10.1016/j.quascirev.2015.12.020>
- Feurdean, A., Wohlfarth, B., Björkman, L., Tantau, I., Bennike, O., Willis, K.J., Farcas, S., Robertsson, A.M., 2007. The influence of refugial population on Lateglacial and early Holocene vegetational changes in Romania. *Rev. Palaeobot. Palynol.* 145, 305–320. <https://doi.org/10.1016/j.revpalbo.2006.12.004>
- Folk, R.L., Ward, W.C., 1957. Brazos River bar: a study in the significance of grain size parameters. *J. Sediment. Petrol.* 27, 3–26.
- Gaillard, M.-J., Birks, H.H., 2007. Paleolimnological applications, w: Elias, S.A. (Red.), *Encyclopedia of Quaternary Science*, Volume 3. Elsevier Science, Amsterdam, pp. 2337–2356.
- Gałka, M., Tanțău, I., Feurdean, A., 2017. Plant succession in a peatland in the Eastern Carpathian Mts. (CE Europe) during the last 10,200 years: Implications for peatland development and palaeoclimatic research. *Rev. Palaeobot. Palynol.* 244, 203–216. <https://doi.org/10.1016/j.revpalbo.2017.05.014>
- Gotkiewicz, J., 1973. Wpływ procesu murszenia gleby torfowej na wielkość stosunku azotu azotanowego do amonowego. *Zesz. Probl. Postępów Nauk Rol.* 146, 125–138.
- Gotkiewicz, J., 1983. Zróżnicowanie intensywności mineralizacji azotu w glebach organicznych związane z odrębnością warunków siedliskowych. Instytut Melioracji i Użytków Zielonych, Falenty.
- Grimm, E.C., 1987. CONISS: A FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Comput. Geosci.* 13, 13–35. [https://doi.org/10.1016/0098-3004\(87\)90022-7](https://doi.org/10.1016/0098-3004(87)90022-7)
- Grimm, E.C., 1991. TILIA and TILIA graph. Illinois State Museum, Springfield.
- Harmata, K., 1987. Late-Glacial and Holocene history of vegetation at Roztoki and Tarnowiec near Jasło (Jasło-Sanok Depression). *Acta Palaeobot.* 27, 43–65.

- Heggen, M.P., Birks, H.H., Heiri, O., Grytnes, J.A., Birks, H.J.B., 2012. Are fossil assemblages in a single sediment core from a small lake representative of total deposition of mite, chironomid, and plant macrofossil remains? *J. Paleolimnol.* 48, 669–691. <https://doi.org/10.1007/s10933-012-9637-y>
- Heiri, O., Lotter, A., Lemcke, G., 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *J. Paleolimnol.* 25, 101–110. <https://doi.org/10.1023/A:1008119611481>
- Housley, R.A., MacLeod, A., Nalepka, D., Jurochnik, A., Masojć, M., Davies, L., Lincoln, P.C., Bronk Ramsey, C., Gamble, C.S., Lowe, J.J., 2013. Tephrostratigraphy of a Lateglacial lake sediment sequence at Węgliny, southwest Poland. *Quat. Sci. Rev.* 77, 4–18. <https://doi.org/10.1016/j.quascirev.2013.07.014>
- Hubay, K., Braun, M., Buczkó, K., Pál, I., Veres, D., Túri, M., Biró, T., Magyari, E., 2018. Holocene environmental changes as recorded in the geochemistry of glacial lake sediments from Retezat Mountains, South Carpathians. *Quat. Int.* 477, 19–39. <https://doi.org/10.1016/j.quaint.2018.02.024>
- Iversen, J., 1954. The late-glacial flora of Denmark and its relation to climate and soil. *Danmarks Geol. Undersøgelser II. Række* 80, 87–119.
- Juggins, S., 2022a. riojaPlot: Stratigraphic diagrams in R, package version 0.1-20. <https://github.com/nsj3/riojaPlot> (dostęp 01.04.2023).
- Juggins, S., 2022b. Rioja: Analysis of quaternary science data. R package version 1.0-5, <https://cran.r-project.org/package=rioja> (dostęp 15.03.2023).
- Jurochnik, A., Nalepka, D., 2013. Late Glacial and Holocene plant cover in Węgliny, Lubuska Plain, south-west Poland, based on pollen analysis. *Acta Palaeobot.* 53, 191–233. <https://doi.org/10.2478/acpa-2013-0013>
- Juvigné, E., Gewalt, M., Gilot, E., Hurtgen, C., Zeghedi, I., Szakacs, A., Gabris, G., Hadnagy, A., Horváth, E., 1994. An eruption at about 10,700 yr BP (C-14) in the Eastern Carpathian Mountains (Romania). *Comptes rendus l'Académie des Sci. - Séries IIB - - Mécanique, Phys. Chim. Astron.* 318, 1233–1238.
- Juvigné, E., Kozarski, S., Nowaczyk, B., 1995. The occurrence of Laacher See Tephra in Pomerania, NW Poland. *Boreas* 24, 225–231.
- Kats, N.Y., Kats, S.V., Kipiani, M.G., 1965. Atlas and keys of fruits and seeds occurring in the Quaternary deposits of the USSR [in Russian]. Nauka, Moscow.
- Kłapyta, P., Zasadni, J., Pociask-Karteczka, J., Gajda, A., Franczak, P., 2016. Late Glacial and Holocene paleoenvironmental records in the Tatra Mountains, East-Central Europe, based on lake, peat bog and colluvial sedimentary data: A summary review. *Quat. Int.* 415, 126–144. <https://doi.org/10.1016/j.quaint.2015.10.049>
- Kletetschka, G., Vondrák, D., Hrubá, J., Van der Knaap, W.O., Van Leeuwen, J.F.N., Heurich, M., 2019. Laacher See tephra discovered in the Bohemian Forest, Germany, east of the eruption. *Quat. Geochronol.* 51, 130–139. <https://doi.org/10.1016/j.quageo.2019.02.003>
- Kołaczek, P., Gałka, M., Karpińska-Kołaczek, M., 2015. Succession of arboreal taxa during the Late Glacial in south-eastern Poland: Climatic implications. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 421, 1–14. <https://doi.org/10.1016/j.palaeo.2015.01.007>

- Koperowa, W., 1961. Późnoglacialna i holocenska historia roślinności Kotliny Nowotarskiej. *Acta Palaeobot.* 2, 3–57.
- Körber-Grohne, U., 1964. Bestimmungsschlüssel für subfossile Juncus- Samen und Gramineen- Früchte, w: Haarnagel, W. (Red.), Probleme Der Küstenforschung Im Südlichen Nordseegebiet 7. August Lax, Hildesheim, pp. 1–47.
- Körber-Grohne, U., 1991. Identification key for subfossil Gramineae fruits. *Probl. der Küstenforsch. im Südlichen Nord.* 18, 169–234.
- Kowalewski, G., 2014. Alogeniczne i autogeniczne składowe zarastania jezior: hipoteza wahań poziomu wody, *Studia Limnologica et Telmatologica, Monographiae I. Polskie Towarzystwo Limnologiczne: Bogucki Wydawnictwo Naukowe, Poznań.*
- Książkiewicz, M., 1972. Karpaty, w: Pożaryski, W. (Red.), Budowa Geologiczna Polski, Part IV, Tektonika. Vol. 3, Karpaty. Wydawnictwo Geologiczne, Warszawa, p. 228.
- Książkiewicz, M., Rączkowski, W., Wójcik, A., 2016. Szczegółowa Mapa Geologiczna Polski w skali 1:50000, Arkusz Osielec. Ministerstwo Środowiska, Warszawa.
- Lane, C.S., Andrič, M., Cullen, V.L., Blockley, S.P.E., 2011. The occurrence of distal Icelandic and Italian tephra in the Lateglacial of Lake Bled, Slovenia. *Quat. Sci. Rev.* 30, 1013–1018. <https://doi.org/10.1016/j.quascirev.2011.02.014>
- Lane, C.S., Blockley, S.P.E., Mangerud, J., Smith, V.C., Lohne, S., Tomlinson, E.L., Matthews, I.P., Lotter, A.F., 2012. Was the 12.1ka Icelandic Vedde Ash one of a kind? *Quat. Sci. Rev.* 33, 87–99. <https://doi.org/10.1016/j.quascirev.2011.11.011>
- Latałowa, M., Nalepka, D., 1987. A study of the Late-Glacial and Holocene vegetational history of the Wolbrom area (Silesian-Cracovian Upland). *Acta Palaeobot.* 27, 75–115.
- Levy, E.T., Schlesinger, W.H., 1999. A comparison of fractionation methods for forms of phosphorus in soils. *Biogeochemistry* 47, 25–38.
- Litt, T., Brauer, A., Goslar, T., Merkt, J., Balaga, K., Müller, H., Ralska-Jasiewiczowa, M., Stebich, M., Negendank, J.F.W., 2001. Correlation and synchronisation of Lateglacial continental sequences in northern central Europe based on annually laminated lacustrine sediments. *Quat. Sci. Rev.* 20, 1233–1249. [https://doi.org/10.1016/S0277-3791\(00\)00149-9](https://doi.org/10.1016/S0277-3791(00)00149-9)
- Loeppert, R.H., Suarez, D.L., 1996. Carbonate and gypsum, w: Sparks, D. (Red.), *Methods of Soil Analysis. Part 3. Chemical Methods. SSSA Book Series Vol. 5. SSSA and ASA, Madison, Wisconsin*, pp. 437–474.
- Lotter, A.F., Eicher, U., Siegenthaler, U., Birks, H.J.B., 1992. Late-glacial climatic oscillations as recorded in Swiss lake sediments. *J. Quat. Sci.* 7, 187–204. <https://doi.org/https://doi.org/10.1002/jqs.3390070302>
- Lowe, J.J., Rasmussen, S.O., Björck, S., Hoek, W.Z., Steffensen, J.P., Walker, M.J.C., Yu, Z.C., 2008. Synchronisation of palaeoenvironmental events in the North Atlantic region during the Last Termination: a revised protocol recommended by the INTIMATE group. *Quat. Sci. Rev.* 27, 6–17. <https://doi.org/10.1016/j.quascirev.2007.09.016>
- Magyari, E., 2002. Holocene biogeography of *Fagus sylvatica* L. and *Carpinus betulus* L. in the Carpathian-Alpine Region. *Folia Hist. Musei Matraensis* 26, 15–35.
- Magyari, E.K., Kuneš, P., Jakab, G., Sümegi, P., Pelánková, B., Schäbitz, F., Braun, M., Chytrý,

- M., 2014. Late Pleniglacial vegetation in eastern-central Europe: are there modern analogues in Siberia? *Quat. Sci. Rev.* 95, 60–79.
- Magyari, E.K., Vincze, I., Orbán, I., Bíró, T., Pál, I., 2018. Timing of major forest compositional changes and tree expansions in the Retezat Mts during the last 16,000 years. *Quat. Int.* 477, 40–58. <https://doi.org/10.1016/j.quaint.2017.12.054>
- Mamakowa, K., 1962. Roślinność Kotliny Sandomierskiej w Późnym Glacjale i Holocenie. *Acta Palaeobot.* 3, 3–57.
- Mangerud, J., Andersen, S.T., Berglund, B.E., Donner, J.J., 1974. Quaternary stratigraphy of Norden, proposal for terminology and classification. *Boreas* 3, 109–128.
- Margielewski, W., 2001a. Late Glacial and Holocene climatic changes registered in forms and deposits of the Klakłowo landslide (Beskid Średni Range, Outer Carpathians). *Stud. Geomorphol. Carpatho-Balcanica* 35, 63–79.
- Margielewski, W., 2001b. Rejestr zmian klimatycznych późnego glacjału i holocenu w obrębie torfowiska pod Kotoniem (Beskid Średni, Karpaty Zewnętrzne). *Przegląd Geol.* 49, 1161–1166.
- Margielewski, W., 2006. Records of the Late glacial-Holocene palaeoenvironmental changes in landslide forms and deposits of the Beskid Makowski and Beskid Wyspowy Mts. area (Polish outer Carpathians). *Folia Quat.* 76, 1–149.
- Margielewski, W., 2014. Torfowiska osuwiskowe polskich Karpat fliszowych jako czuły indykator zmian paleośrodowiska późnego glacjału i holocenu. *Stud. Limnol. Telmatologic* 8/1, 37–55.
- Margielewski, W., 2018. Landslide fens as a sensitive indicator of paleoenvironmental changes since the Late Glacial: A case study of the Polish Western Carpathians. *Radiocarbon* 60, 1199–1213. <https://doi.org/10.1017/RDC.2018.68>
- Margielewski, W., Michczyńska, D.J., Buczek, K., Michczyński, A., Korzeń, K., Obidowicz, A., 2022a. Towards the understanding of the present-day human impact on peatland deposits formed since the Late Glacial: a retrospective age-depth model of the Grel raised bog (Polish Inner Carpathians). *Radiocarbon* 64, 1525–1543. <https://doi.org/10.1017/RDC.2022.62>
- Margielewski, W., Michczyński, A., Obidowicz, A., 2010. Records of the middle - and Late Holocene palaeoenvironmental changes in the Pcim-Sucha landslide peat bogs (Beskid Makowski Mts., Polish Outer Carpathians). *Geochronometria* 35, 11–23. <https://doi.org/10.2478/v10003-010-0009-1>
- Margielewski, W., Obidowicz, A., Pelc, S., 2003. Late Glacial-Holocene peat bog on Kotoń Mt. and its significance for reconstruction of palaeoenvironment in the Western Outer Carpathians (Beskid Makowski Range, South Poland). *Folia Quat.* 74, 35–56.
- Margielewski, W., Obidowicz, A., Zernitskaya, V., Korzeń, K., 2022b. Late Glacial and Holocene palaeoenvironmental changes recorded in landslide fens deposits in the Polish Outer Western Carpathians (Southern Poland). *Quat. Int.* 616, 67–86. <https://doi.org/10.1016/j.quaint.2021.11.001>
- Mauquoy, D., Van Geel, B., 2007. Mire and peat macros, w: Elias, S.A. (Red.), *Encyclopedia of Quaternary Science, Volume 3*. Elsevier Science, Amsterdam, pp. 2315–2336. <https://doi.org/10.1016/B0-44-452747-8/00229-5>

- Michczyński, A., Kołaczek, P., Margielewski, W., Michczyńska, D.J., Obidowicz, A., 2013. Radiocarbon age-depth modeling prevents misinterpretation of past vegetation dynamics: Case study of Wierchomla Mire (Polish Outer Carpathians). *Radiocarbon* 55, 1724–1734. <https://doi.org/10.1017/s0033822200048645>
- Mirek, Z., Piękoś-Mirkowa, H., Zając, A., Zając, M., 2020. Vascular plants of Poland. An annotated checklist. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków.
- Moore, P.D., Webb, J.A., Collinson, M.E., 1991. *Pollen Analysis*. Blackwell Scientific Publications, Oxford.
- Moriya, I., Okuno, M., Nakamura, T., Ono, K., Szakacs, A., I., S., 1996. Radiocarbon ages of charcoal fragments from the pumice flow deposit of the last eruption of Ciomadul volcano, Romania (in Japanese with English Abstract). *Summ. Res. Using AMS Nagoya Univ.* VII, 252–255.
- Moska, P., Sokołowski, R.J., Jary, Z., Zieliński, P., Raczyk, J., Szymak, A., Krawczyk, M., Skurzyński, J., Poręba, G., Łopuch, M., Tudyka, K., 2022. Stratigraphy of the Late Glacial and Holocene aeolian series in different sedimentary zones related to the Last Glacial maximum in Poland. *Quat. Int.* 630, 65–83. <https://doi.org/10.1016/j.quaint.2021.04.004>
- Nakagawa, T., Brugiapaglia, E., Digerfeldt, G., Reille, M., de Beaulieu, J.-L., Yasuda, Y., 1998. Dense-media separation as a more efficient pollen extraction method for use with organic sediment/deposit samples: comparison with the conventional method. *Boreas* 27, 15–24.
- Nalepka, D., 1994. The history of vegetation in the western part of Sandomierz Basin during the last 15 000 years. *Wiadomości Bot.* 38, 95–105.
- Nalepka, D., 2005. Late Glacial and Holocene palaeoecological conditions and changes of vegetation cover under early farming activity in the south Kujawy region (central Poland). *Acta Palaeobot. Suppl.* 6, 1–93.
- Nalepka, D., Walanus, A., 2003. Data processing in pollen analysis. *Acta Palaeobot.* 43, 125–134.
- Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon, and organic matter, w: Sparks, D. (Red.), *Methods of Soil Analysis. Part 3. Chemical Methods*. SSSA Book Series Vol. 5. SSSA and ASA, Madison, Wisconsin, pp. 961–1010.
- Novik, A., Punning, J.-M., Zernitskaya, V., 2010. The development of Belarusian lakes during the Late Glacial and Holocene. *Est. J. Earth Sci.* 59, 63–79. <https://doi.org/10.3176/earth.2010.1.05>
- Obidowicz, A., 1993. Wahania górnej granicy lasu w późnym plejstocenie i holocenie w Tatrach, w: Kotarba, A. (Red.), *Dokumentacja Geograficzna. Z Badań Fizyczno-Geograficznych w Tatrach*. Instytut Geografii i Przestrzennego Zagospodarowania PAN, Warszawa, pp. 31–43.
- Obidowicz, A., 1996. A Late Glacial-Holocene history of the formation of vegetation belts in the Tatra Mts. *Acta Palaeobot.* 36, 159–206.
- PalDat: Palynological Database, 2000. <https://www.paldat.org> (dostęp 01.10.2025).
- Pánek, T., Hradecký, J., Smolková, V., Šilhán, K., Minár, J., Zernitskaya, V., 2010. The largest prehistoric landslide in northwestern Slovakia: Chronological constraints of the Kykula long-runout landslide and related dammed lakes. *Geomorphology* 120, 233–247.

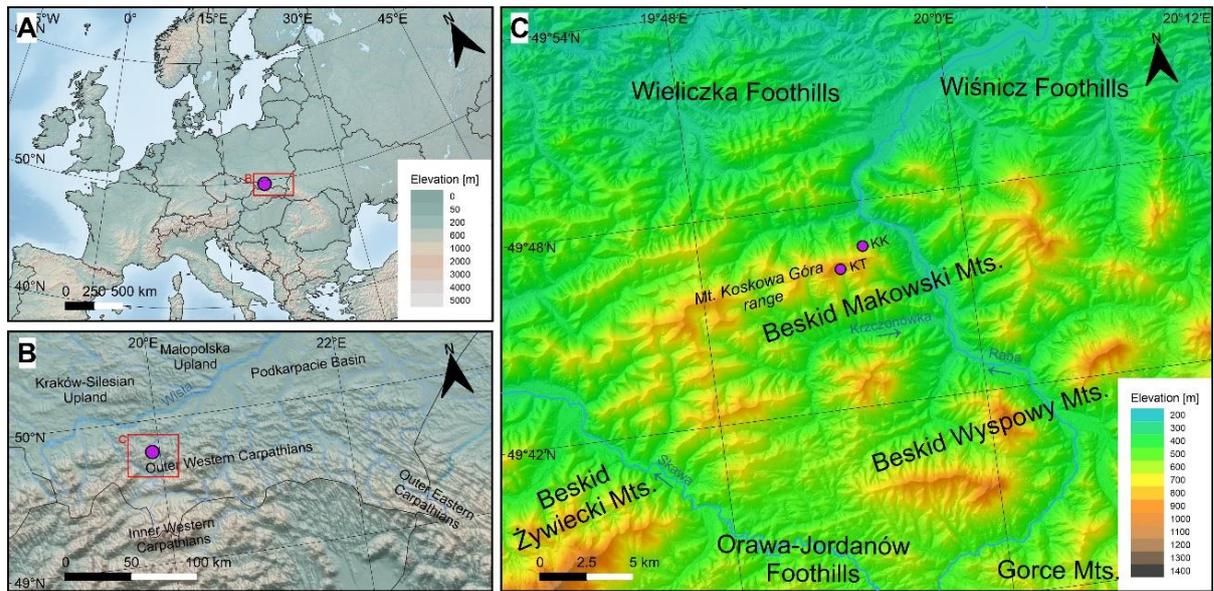
<https://doi.org/10.1016/j.geomorph.2010.03.033>

- Passega, R., Byramjee, R., 1969. Grain size image of clastic deposits. *Sedimentology* 13, 233–252.
- Posit Team, 2025. RStudio: Integrated Development Environment for R. Posit Software, PBC, Boston, MA. <http://www.posit.co/>.
- R Core Team, 2022. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria, <https://www.R-project.org/> (dostęp 15.03.2023).
- Ralska-Jasiewiczowa, M., 1980. Late-Glacial and Holocene vegetation of the Bieszczady Mts. (Polish Eastern Carpathians), *Polska Akademia Nauk Instytut Botaniki. Państwowe Wydawnictwo Naukowe, Warszawa-Kraków*.
- Ralska-Jasiewiczowa, M., Demske, D., Van Geel, B., 1998. Late-Glacial vegetation history recorded in the Lake Gościąg sediments, w: Ralska-Jasiewiczowa, M., Goslar, T., Madeyska, E., Starkel, L. (Red.), *Lake Gościąg, Central Poland. A Monographic Study. Part 1. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków*, pp. 128–143.
- Rasmussen, S.O., Bigler, M., Blockley, S.P., Blunier, T., Buchardt, S.L., Clausen, H.B., Cvijanovic, I., Dahl-Jensen, D., Johnsen, S.J., Fischer, H., Gkinis, V., Guillevic, M., Hoek, W.Z., Lowe, J.J., Pedro, J.B., Popp, T., Seierstad, I.K., Steffensen, J.P., Svensson, A.M., Vallelonga, P., Vinther, B.M., Walker, M.J.C., Wheatley, J.J., Winstrup, M., 2014. A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: Refining and extending the INTIMATE event stratigraphy. *Quat. Sci. Rev.* 106, 14–28. <https://doi.org/10.1016/j.quascirev.2014.09.007>
- Reille, M., 1992. *Pollen et spores d'Europe et d'Afrique du Nord. Laboratoire de Botanique Historique et Palynologie, Marseille*.
- Reimer, P.J., Austin, W.E.N., Bard, E., Bayliss, A., Blackwell, P.G., Bronk Ramsey, C., Butzin, M., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kromer, B., Manning, S.W., Muscheler, R., Palmer, J.G., Pearson, C., Van Der Plicht, J., Reimer, R.W., Richards, D.A., Scott, E.M., Southon, J.R., Turney, C.S.M., Wacker, L., Adolphi, F., Büntgen, U., Capano, M., Fahrni, S.M., Fogtmann-Schulz, A., Friedrich, R., Köhler, P., Kudsk, S., Miyake, F., Olsen, J., Reinig, F., Sakamoto, M., Sookdeo, A., Talamo, S., 2020. The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon* 62, 725–757. <https://doi.org/10.1017/RDC.2020.41>
- Rubensdotter, L., Rosqvist, G., 2003. The effect of geomorphological setting on Holocene lake sediment variability, northern Swedish Lapland. *J. Quat. Sci.* 18, 757–767. <https://doi.org/10.1002/jqs.800>
- Rybničková, E., Rybniček, K., 1991. The environment of the Pavlovian: palaeoecological results from Bulhary, South Moravia, in: *Palaeovegetational Development in Europe, Proceedings of the Pan-European Palaeobotanical Conference 1991. Museum of Natural History, Vienna*, pp. 73–79.
- Salmon, V.G., Brice, D.J., Bridgham, S., Childs, J., Graham, J., Griffiths, N.A., Hanson, P.J., 2021. Nitrogen and phosphorus cycling in an ombrotrophic peatland: a benchmark for assessing change. *Plant Soil* 466, 649–674.

- Saxby, J., Rust, A., Cashman, K., Beckett, F., 2020. The importance of grain size and shape in controlling the dispersion of the Vedde cryptotephra. *J. Quat. Sci.* 35, 175–185. <https://doi.org/10.1002/jqs.3152>
- Schmidt, R., Van Den Bogaard, C., Merkt, J., Müller, J., 2002. A new Lateglacial chronostratigraphic tephra marker for the south-eastern Alps: The Neapolitan Yellow Tuff (NYT) in Längsee (Austria) in the context of a regional biostratigraphy and palaeoclimate. *Quat. Int.* 88, 45–56. [https://doi.org/10.1016/S1040-6182\(01\)00072-6](https://doi.org/10.1016/S1040-6182(01)00072-6)
- Shumilovskikh, L.S., Shumilovskikh, E.S., Schlütz, F., & Van Geel, B., 2022. NPP-ID: Non-Pollen Palynomorph Image Database as a research and educational platform. *Veg. Hist. Archaeobot.* 31, 323–328. <https://doi.org/https://doi.org/10.1007/s00334-021-00849-8>
- Šimová, A., Pánek, T., Gałka, M., Zernitskaya, V., Hájková, P., Brodská, H., Jamrichová, E., Hájek, M., 2019. Landslides increased Holocene habitat diversity on a flysch bedrock in the Western Carpathians. *Quat. Sci. Rev.* 219, 68–83. <https://doi.org/10.1016/j.quascirev.2019.07.009>
- Solon, J., Borzyszkowski, J., Bidłasik, M., Richling, A., Badora, K., Balon, J., Brzezińska-Wójcik, T., Chabudziński, Ł., Dobrowolski, R., Grzegorzczak, I., Jodłowski, M., Kistowski, M., Kot, R., Krąż, P., Lechnio, J., Macias, A., Majchrowska, A., Malinowska, E., Migoń, P., Myga-Piątek, U., Nita, J., Papińska, E., Rodzik, J., Strzyż, M., Terpiłowski, S., Ziaja, W., 2018. Physico-geographical mesoregions of Poland: Verification and adjustment of boundaries on the basis of contemporary spatial data. *Geogr. Pol.* 91, 143–170.
- Stuchlik, L., 1994. Some late Pliocene and early Pleistocene pollen profiles from Poland, w: Boulter, M.C., Fisher, H.C. (Red.), *Cenozoic Plants and Climates of the Arctic*. Springer, Berlin–Heidelberg, pp. 371–382.
- Szakács, A., Seghedi, I., Pécskay, Z., 2002. The most recent volcanism in the Carpathian-Pannonian Region. Is there any volcanic hazard?, in: *Geologica Carpathica Special Issue, Proceedings of the XVIIth Congress of Carpatho-Balkan Geological Association*. p. 53.
- Szymczyk, A., 2012. Relations between assemblages of carpological remains and modern vegetation in a shallow reservoir in southern Poland. *J. Paleolimnol.* 48, 503–516. <https://doi.org/10.1007/s10933-012-9627-0>
- Tołpa, S., Jasnowski, M., Pałczyński, A., 1967. System genetyczny klasyfikacji torfów występujących w złożach Europy Środkowej. *Zesz. Probl. Postępów Nauk Rol.* 76, 27–99.
- Tomczyk, A.M., Bednorz, E. (Red.), 2022. *Atlas klimatu Polski (1991-2020)*. Bogucki Wydawnictwo Naukowe, Poznań.
- Van Geel, B., 1978. A palaeoecological study of Holocene peat bog section in Germany and The Netherlands, based on the analysis of pollen, spores and macro- and microscopic remains of fungi, algae, coprophites and animals. *Rev. Palaeobot. Palynol.* 25, 1–120.
- Van Geel, B., Bohncke, S.J.P., Dee, H., 1980. A palaeoecological study of an upper Late Glacial and Holocene sequence from “De Borchert”, The Netherlands. *Rev. Palaeobot. Palynology* 31, 367–448.
- Van Geel, B., Buurman, J., Brinkkemper, O., Schelvis, J., Aptroot, A., Van Reenen, G., Hakbijl, T., 2003. Environmental reconstruction of a Roman Period settlement site in Uitgeest (The

- Netherlands), with special reference to coprophilous fungi. *J. Archaeol. Sci.* 30, 873–883.
- Van Geel, B., Zazula, G.D., Schweger, C.E., 2007. Spores of coprophilous fungi from under the Dawson tephra (25 300 14C years BP), Yukon Territory, northwestern Canada. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 252, 481–485.
- Van Raden, U.J., Colombaroli, D., Gilli, A., Schwander, J., Bernasconi, S.M., Van Leeuwen, J., Leuenberger, M., Eicher, U., 2013. High-resolution late-glacial chronology for the Gerzensee lake record (Switzerland): $\delta^{18}\text{O}$ correlation between a Gerzensee-stack and NGRIP. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 391, 13–24. <https://doi.org/10.1016/j.palaeo.2012.05.017>
- Velichkevich, F., Zastawniak, E., 2006. Atlas of the Pleistocene vascular plant macrofossils of Central and Eastern Europe. Part 1: Pteridophytes and Monocotyledons. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków.
- Velichkevich, F., Zastawniak, E., 2008. Atlas of the Pleistocene vascular plant macrofossils of Central and Eastern Europe. Part 2: Herbaceous Dicotyledones. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków.
- Wang, D., Zang, S., Wang, L., Ma, D., Li, M., 2022. Effects of permafrost degradation on soil carbon and nitrogen cycling in permafrost wetlands. *Front. Earth Sci.* 10, 1–10. <https://doi.org/10.3389/feart.2022.911314>
- Wasylikowa, K., 1964. Roślinność i klimat późnego glacjału w środkowej Polsce na podstawie badań w Witowie koło Łęczycy. *Biul. Peryglac.* 13, 261–417.
- Watts, W.A., 1980. Regional variation in the response of vegetation to Lateglacial climatic events in Europe, w: Lowe, J.J., Gray, J.M., Robinson, J.E. (Red.), *Studies in the Late-Glacial of North-West Europe*. Pergamon Press, Oxford, p. 205.
- Welten, M., 1982. Vegetationsgeschichtliche Untersuchungen in den westlichen Schweizer Alpen: Bern-Wallis, in: *Denkschriften Der Schweizerischen Naturforschenden Gesellschaft*. Birkhäuser Verlag, Basel, pp. 1–104.
- Willis, K.J., Van Andel, T.H., 2004. Trees or no trees? The environments of central and eastern Europe during the Last Glaciation. *Quat. Sci. Rev.* 23, 2369–2387. <https://doi.org/10.1016/j.quascirev.2004.06.002>
- Winter, H., 2015. Dynamika zmian klimatycznych w pliocenie i plejstocenie dolnym oraz granica neogen/czwartorzęd w osadach z południowego Mazowsza (środkowa Polska) na podstawie danych palinologicznych. *Pr. Państwowego Inst. Geol.* 202, 53–106.
- Wulf, S., Ott, F., Słowiński, M., Noryskiewicz, A.M., Dräger, N., Martin-Puertas, C., Czymzik, M., Neugebauer, I., Dulski, P., Bourne, A.J., Błaszczewicz, M., Brauer, A., 2013. Tracing the Laacher See Tephra in the varved sediment record of the Trzechowskie palaeolake in central Northern Poland. *Quat. Sci. Rev.* 76, 129–139.
- Zarzycki, K., 2002. Ecological indicator values of vascular plants of Poland. Polish Academy of Sciences, W Szafer Institute of Botany, Kraków.
- Zernitskaya, V., 1997. The evolution of lakes in the Poles`ye in the Late Glacial and Holocene. *Quat. Int.* 41–42, 153–160. [https://doi.org/10.1016/S1040-6182\(96\)00047-X](https://doi.org/10.1016/S1040-6182(96)00047-X)

12. Figurey



Klaklowo

Kotoń

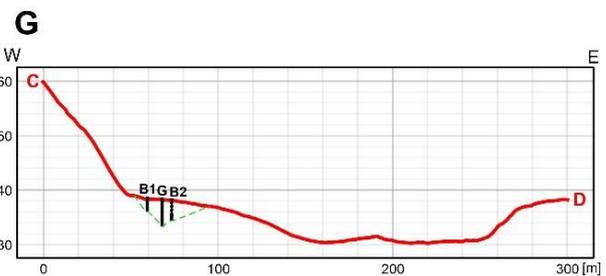
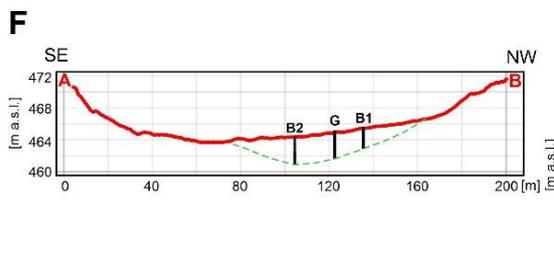
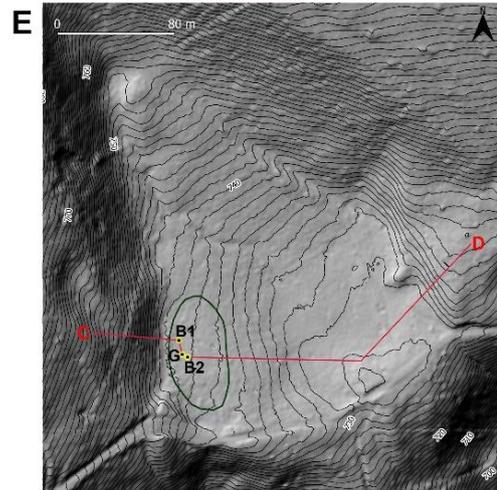
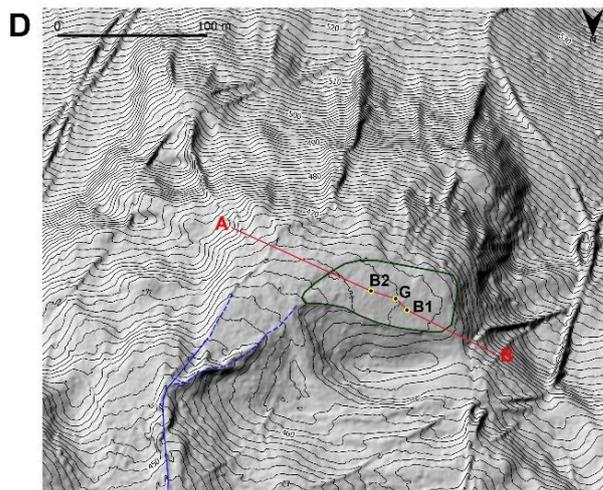


Figura 1. Położenie torfowisk osuwiskowych Klaklowo (KK) i Kotoń (KT) w Europie (A), w regionie Zewnętrznych Karpat Zachodnich (B) i na obszarze Beskidu Makowskiego (C); D) lokalizacja wierzeń w obrębie torfowiska osuwiskowego Klaklowo wraz z linią przekroju AB; E) lokalizacja wierzeń w obrębie torfowiska osuwiskowego Kotoń wraz z linią przekroju CD; F) przekrój AB przez torfowisko Klaklowo wraz z lokalizacjami wierzeń; G) przekrój CD przez

torfowisko Kotoń wraz z lokalizacjami wierceń. Oznaczenia: G – rdzeń główny; B1 – rdzeń boczny; B2 – rdzeń boczny dodatkowy; zielona ciągła linia – współczesny zasięg torfowiska; zielona przerywana linia – teoretyczny zasięg wgłębny zagłębienia osuwiskowego wypełnionego osadami minerogeniczno-organicznymi torfowiska.

Źródła map bazowych: część A) <https://www.naturalearthdata.com/downloads/10m-cross-blend-hypso/cross-blended-hypso-with-relief-water-drains-and-ocean-bottom/>; część B) numeryczny model terenu (NMT) <https://download.gebco.net/> z nałożoną mapą bazową części A); część C), D) i E) NMT z serwisu WCS service <https://mapy.geoportal.gov.pl/wss/service/PZGIK/NMT/GRID1/WCS/DigitalTerrainModelFormatTIFF>. Mapy A, B i C są rzutowane w geometrii stożkowej Lamberta (ETRS89); szerokość i długość geograficzna zgodnie z układem odniesienia współrzędnych geograficznych (ETRS89).

KLAKŁOWO LATERAL CORE B1 - POLLEN DIAGRAM

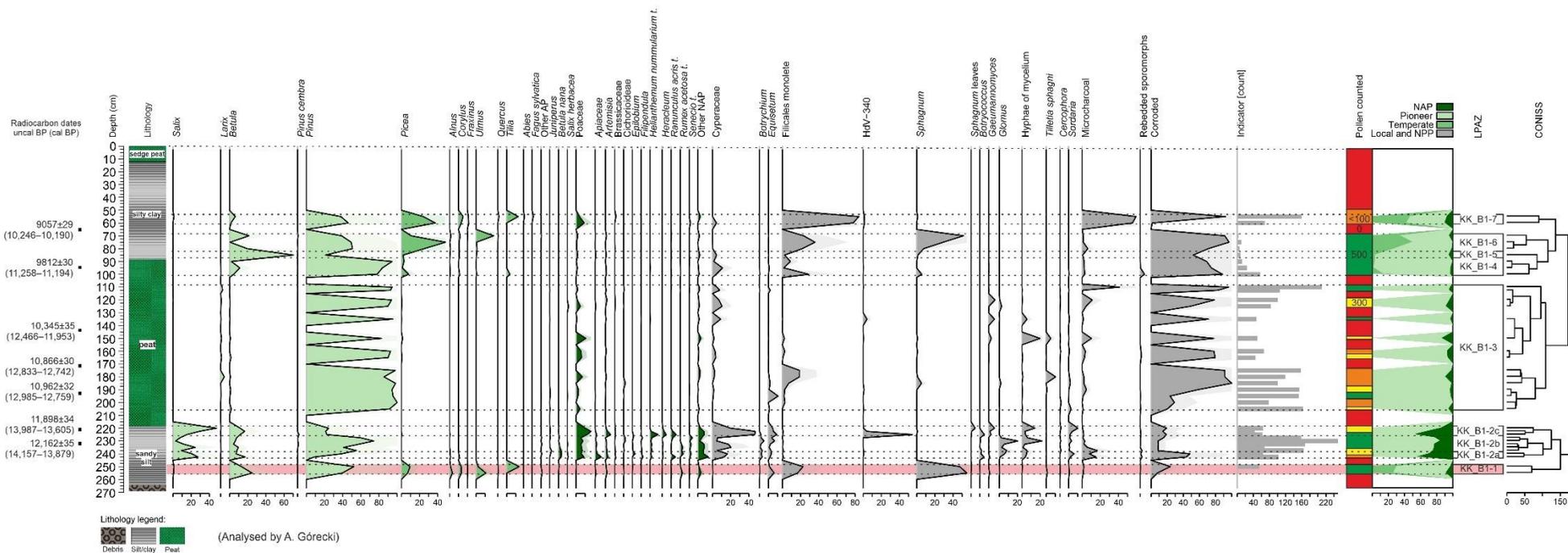
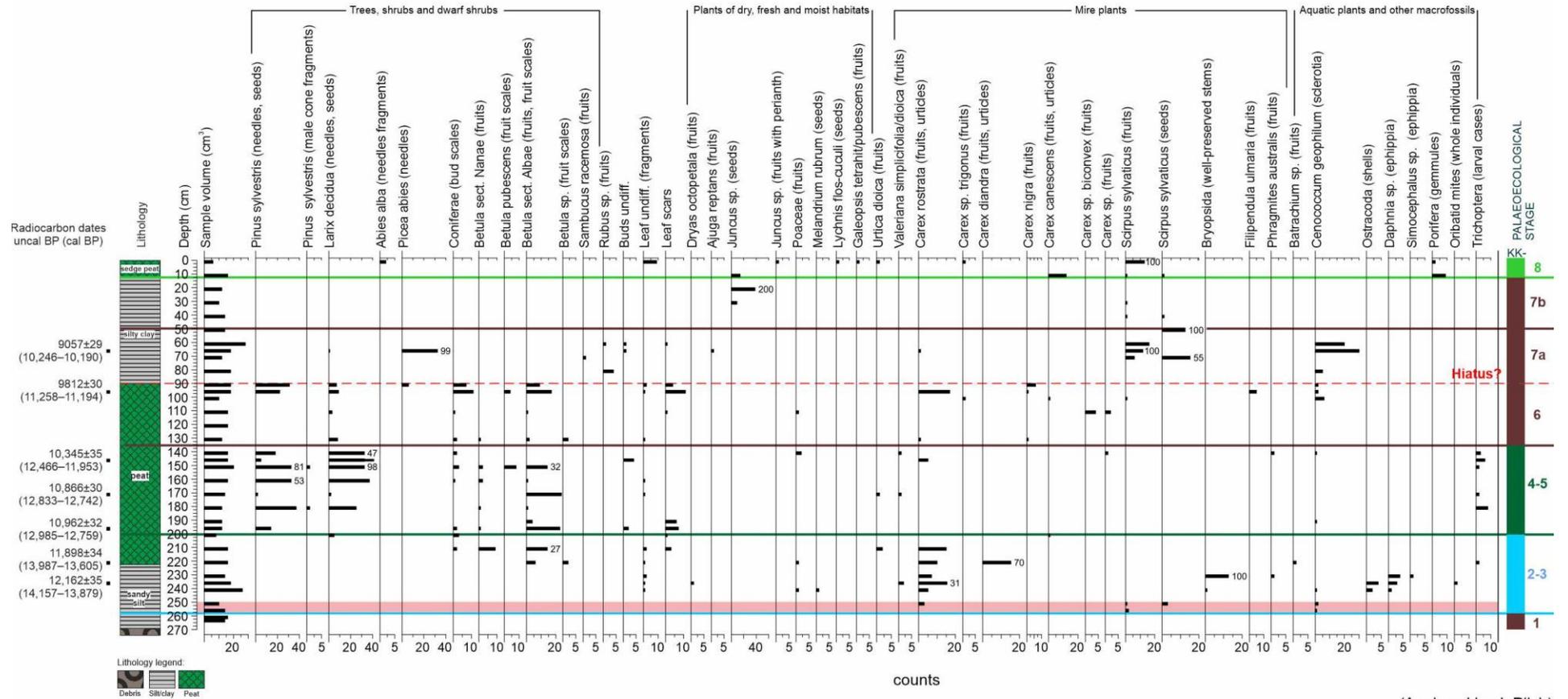


Figura 2. Diagram palinologiczny osadów rdzenia bocznego Klakłowo B1 podzielony na strefy LPAZ. Różowy obszar na diagramie – zasięg głębokościowy występowania w osadach pyłku roślin ciepłolubnych. Wiek skalibrowany (cal BP) podany dla zakresu 2σ (95.4%).

KLAKLOWO LATERAL CORE B1 - PLANT MACROFOSSIL DIAGRAM



(Analysed by J. Pilch)

Figura 3. Diagram makroszczątków roślin osadów rdzenia bocznego Klaklowo B1 podzielony na lokalne etapy rozwoju paleoekologicznego torfowiska. Wartości danych makroszczątkowych zaprezentowane są jako liczebność makroszczątków danego taksonu na próbkę. Różowy obszar na diagramie – zasięg głębokościowy występowania pyłku roślin ciepłolubnych. Wiek skalibrowany (cal BP) podany dla zakresu 2σ (95.4%).

KLAKLOWO LATERAL CORE B2 - POLLEN DIAGRAM

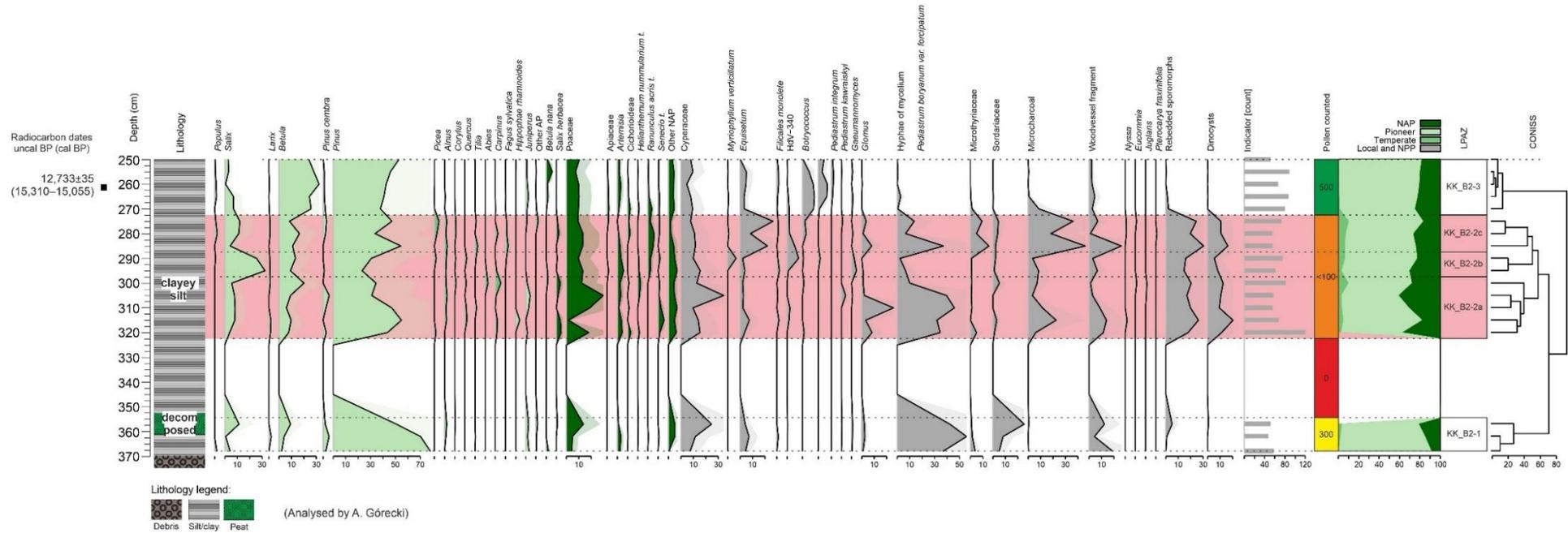


Figura 4. Diagram palinologiczny osadów rdzenia bocznego Klaklowo B2 podzielony na strefy LPAZ. Różowy obszar na diagramie – zasięg głębokościowy występowania w osadach pyłku roślin ciepłolubnych. Wiek skalibrowany (cal BP) podany dla zakresu 2σ (95.4%).

KLAKLOWO LATERAL CORE B2 - PLANT MACROFOSSIL DIAGRAM

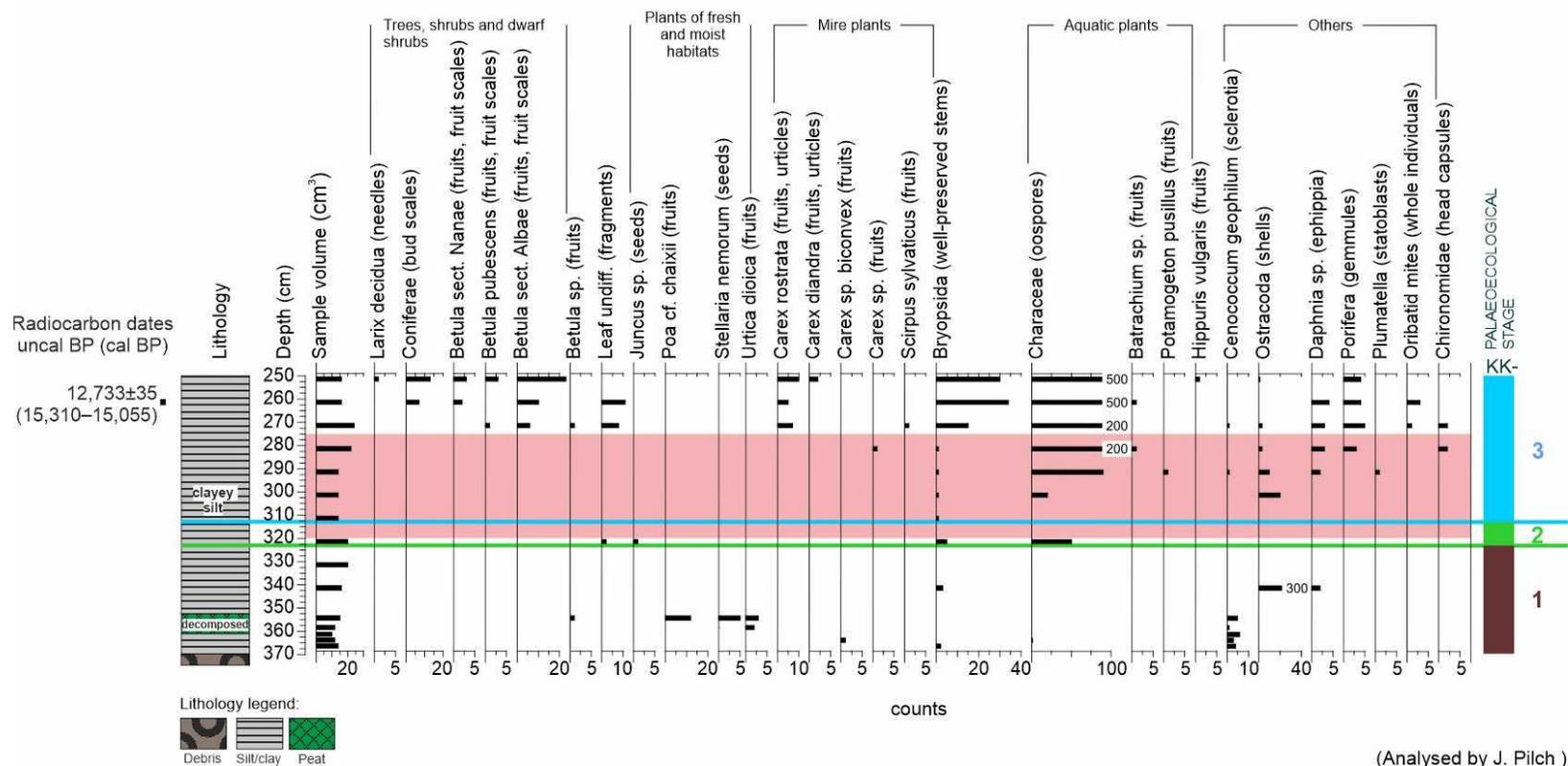


Figura 5. Diagram makroszczątków roślin osadów rdzenia bocznego Klaklowo B2 podzielony na lokalne etapy rozwoju paleoekologicznego torfowiska. Wartości danych makroszczątkowych zaprezentowane są jako liczebność makroszczątków danego taksonu na próbkę. Różowy obszar na diagramie – zasięg głębokościowy występowania w osadach pyłku roślin ciepłolubnych. Wiek skalibrowany (cal BP) podany dla zakresu 2σ (95.4%).

KOTOŃ LATERAL CORE B1 - POLLEN DIAGRAM

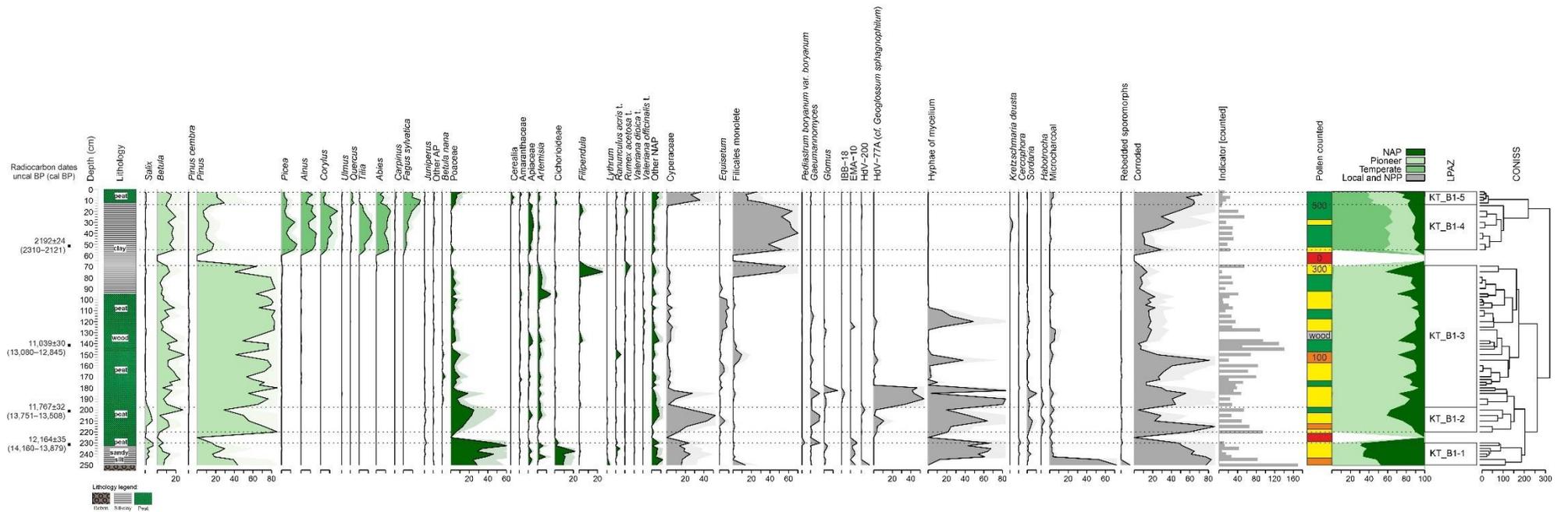


Figura 6. Diagram palinologiczny osadów rdzenia bocznego Kotoń B1 podzielony na strefy LPAZ. Wiek skalibrowany (cal BP) podany dla zakresu 2σ (95.4%).

KOTOŃ LATERAL CORE B1 - PLANT MACROFOSSIL DIAGRAM

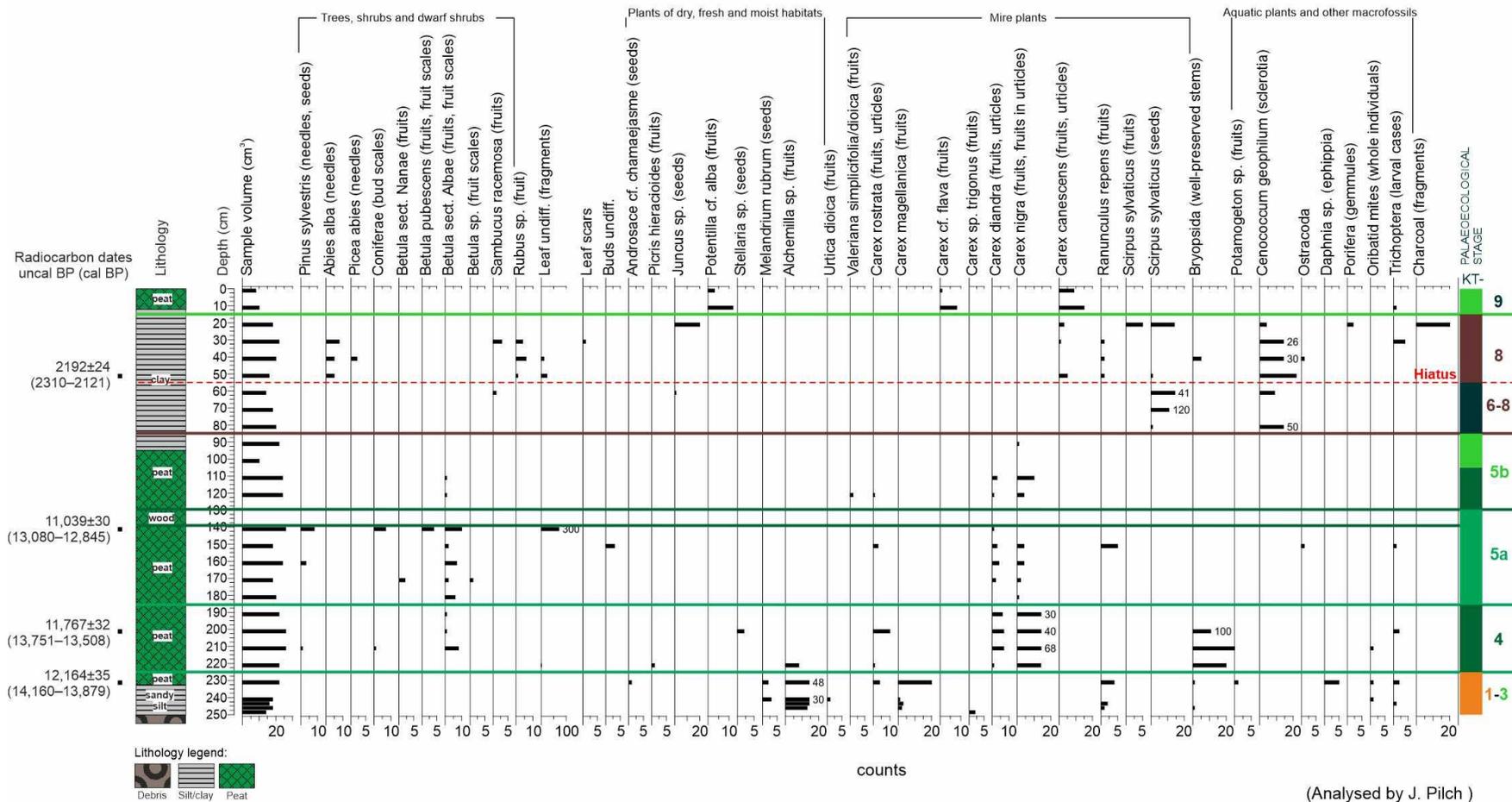


Figura 7. Diagram makroszczątków roślin osadów rdzenia bocznego Kotoń B1 podzielony na lokalne etapy rozwoju paleoekologicznego torfowiska. Wartości danych makroszczątkowych zaprezentowane są jako liczebność makroszczątków danego taksonu na próbkę. Wiek skalibrowany (cal BP) podany dla zakresu 2σ (95.4%).

KOTOŃ LATERAL CORE B2 - POLLEN DIAGRAM

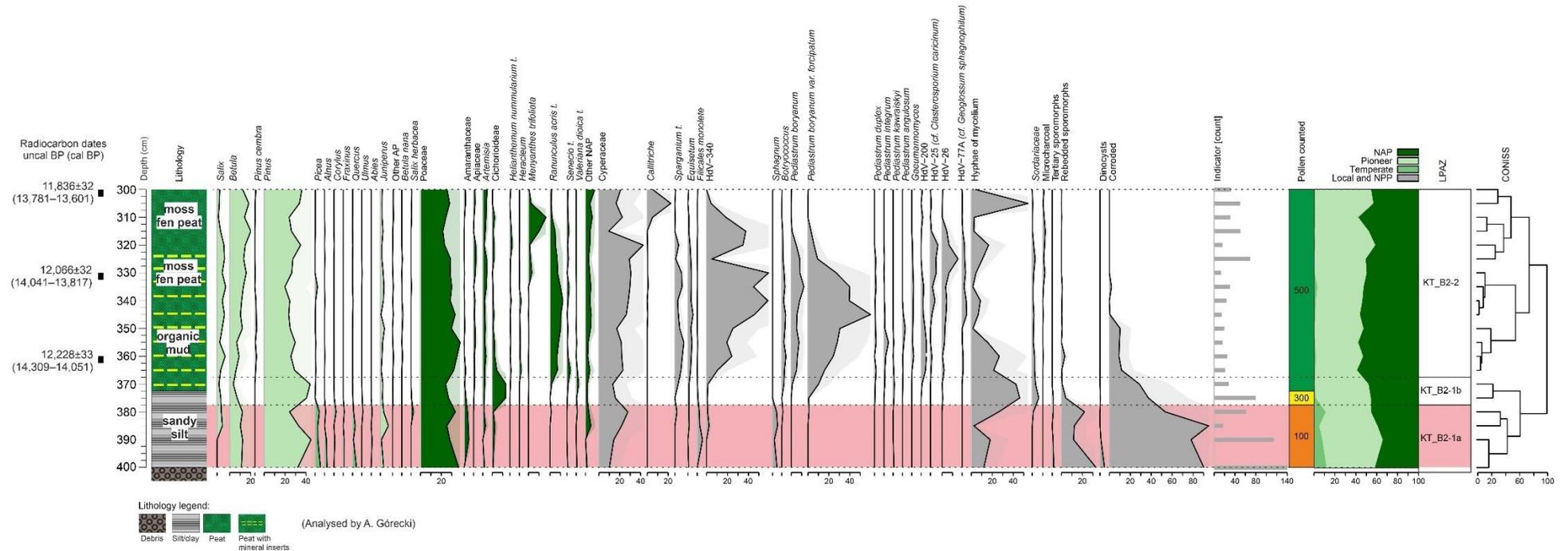


Figura 8. Diagram palinologiczny osadów rdzenia bocznego Kotoń B2 podzielony na strefy LPAZ. Różowy obszar na diagramie – zasięg głębokościowy występowania w osadach pyłku roślin ciepłolubnych. Wiek skalibrowany (cal BP) podany dla zakresu 2σ (95.4%).

KOTOŃ LATERAL CORE B2 - PLANT MACROFOSSIL DIAGRAM

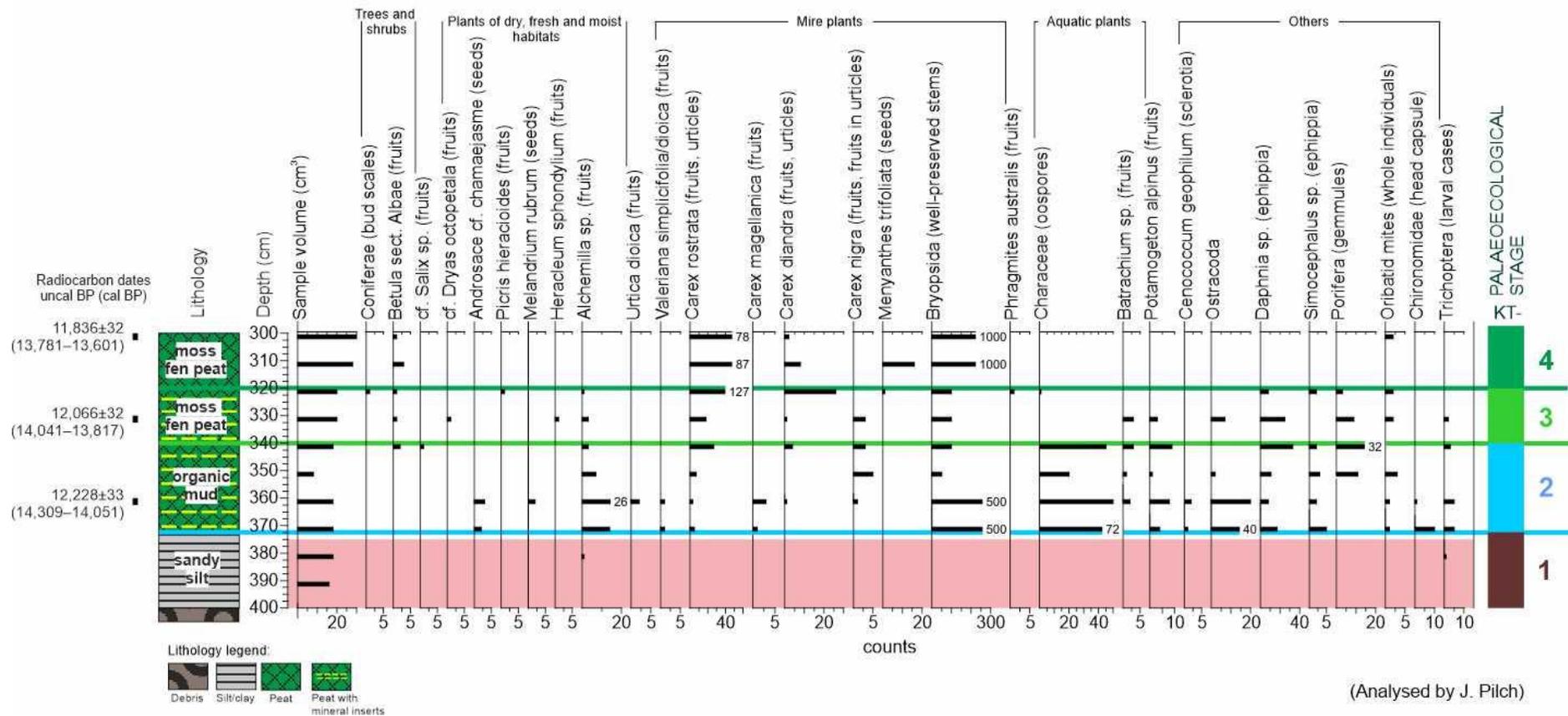


Figura 9. Diagram makroszczątków roślin osadów rdzenia bocznego Kotoń B2 podzielony na lokalne etapy rozwoju paleoekologicznego torfowiska. Wartości danych makroszczątkowych zaprezentowane są jako liczebność makroszczątków danego taksonu na próbkę. Różowy obszar na diagramie – zasięg głębokościowy występowania w osadach pyłku roślin ciepłolubnych. Wiek skalibrowany (cal BP) podany dla zakresu 2σ (95.4%).

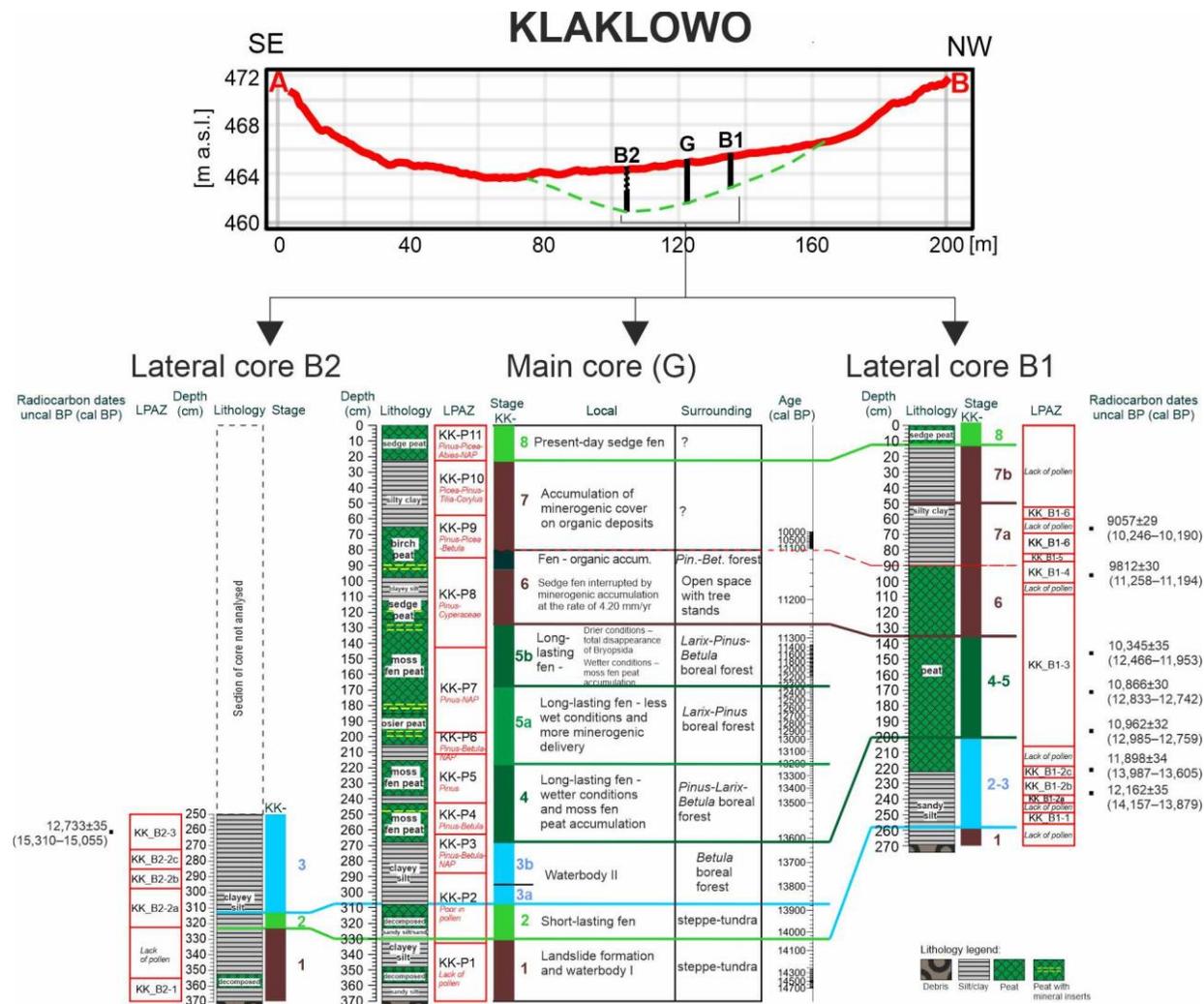


Figura 10. Zestawienie etapów paleoekologicznego rozwoju torfowiska osuwiskowego Klaklowo dla głównego (G, centralna część torfowiska) i bocznych (B1 i B2, marginane części torfowiska) rdzeni osadów. Przebieg linii przekroju AB na Figurze 1 D. Daty radiowęglowe skalibrowane (cal BP) podane dla zakresu 2σ (95.4%).

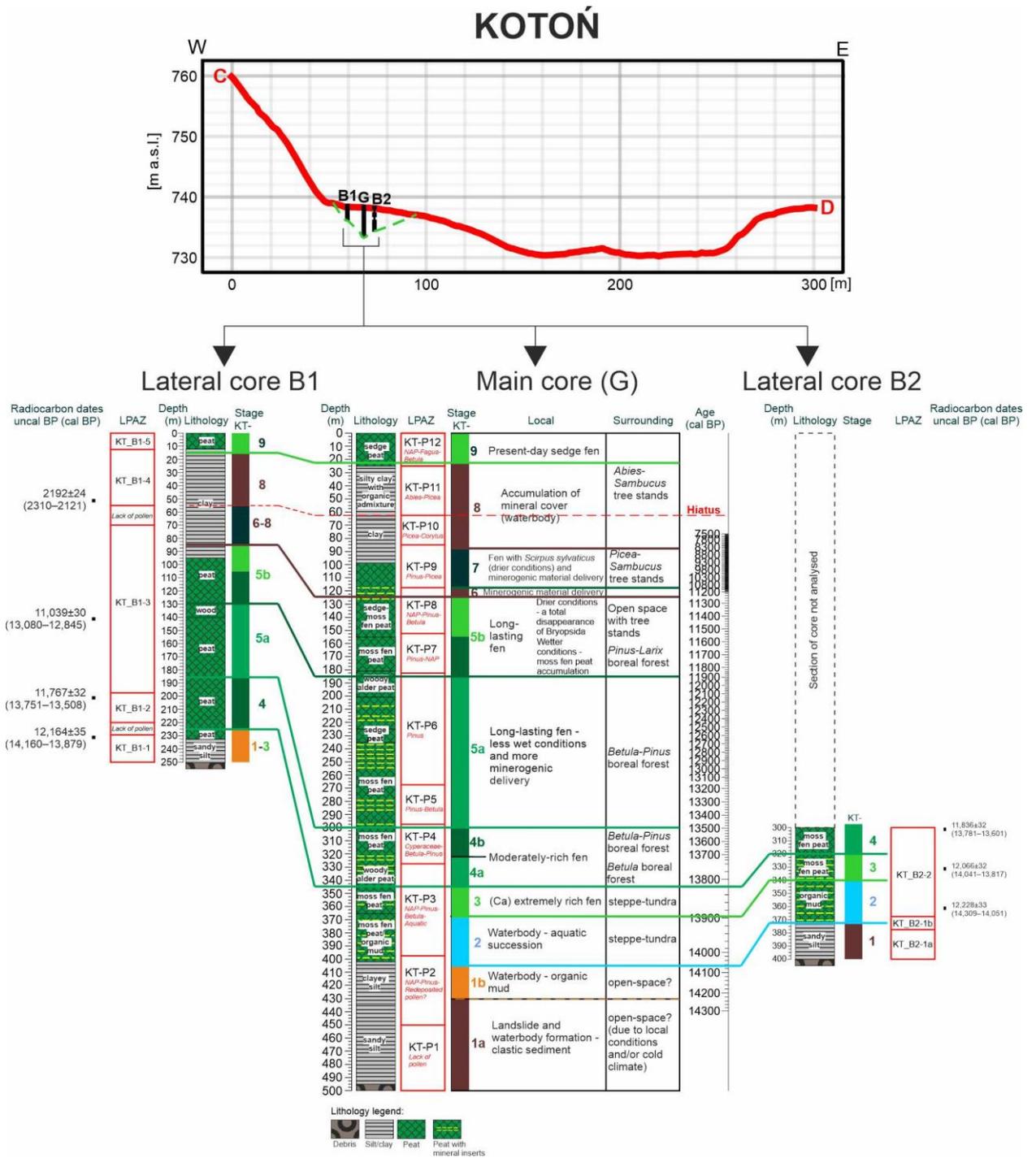


Figura 11. Zestawienie etapów paleoekologicznego rozwoju torfowiska osuwiskowego Kotoń dla głównego (G, centralna część torfowiska) i bocznych (B1 i B2, marginalne części torfowiska) rdzeni osadów. Przebieg linii przekroju CD na Figurze 1 E. Daty radiowęglowe skalibrowane (cal BP) podane dla zakresu 2σ (95.4%).

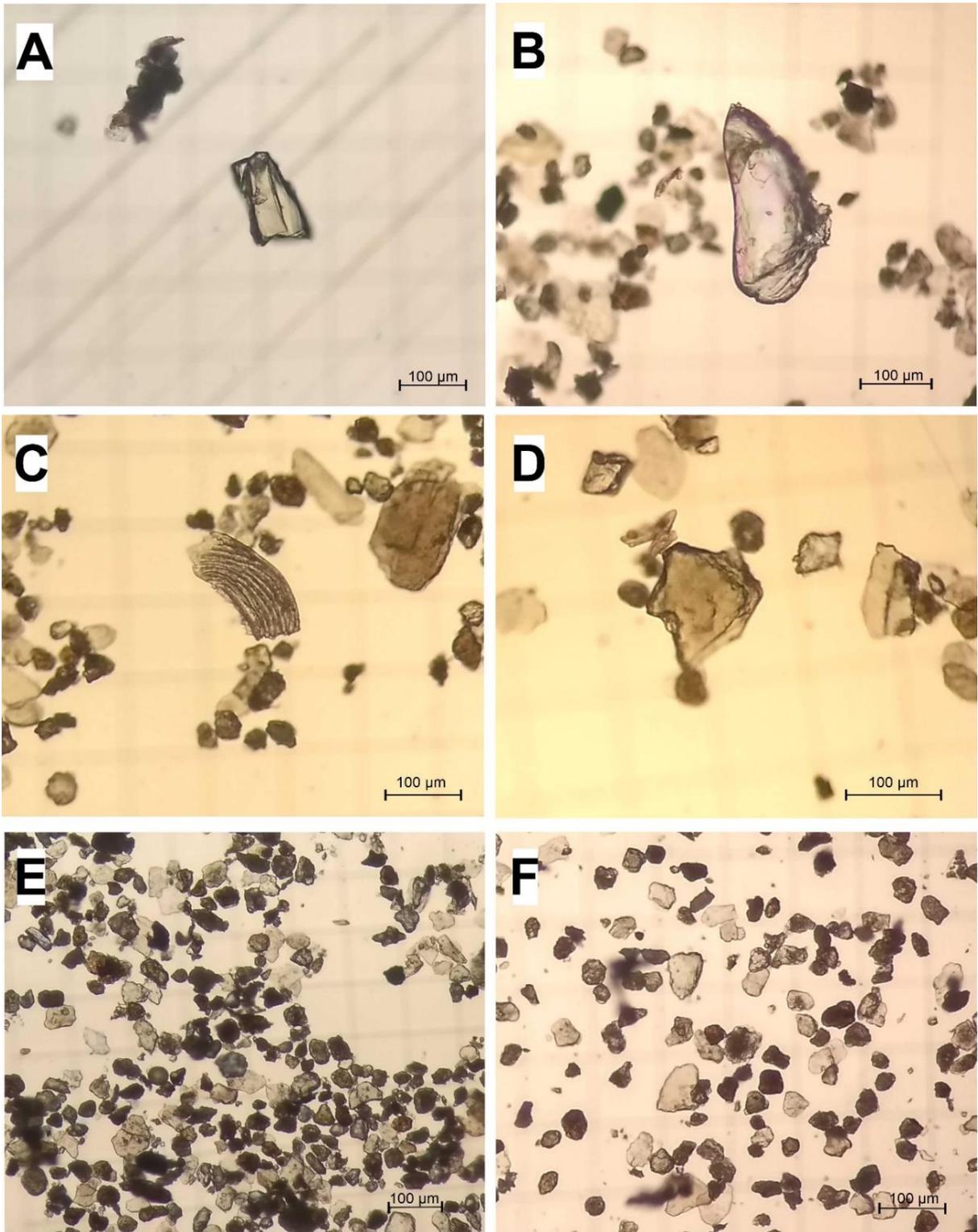


Figura 12. A–D) Zdjęcia pod mikroskopem w świetle przechodzącym (1x) przykładowych ziaren mogących stanowić potencjalne ziarna tefry z przedziału głębokości Neapolitan Yellow Tuff (NYT) profilu osadów Klakłowa. Próbkę z głębokości: A) 335–335,5 cm; B) 332,5–333 cm; C) 332,5–333 cm; D) 333–333,5 cm. E–F) Zdjęcia pod mikroskopem w świetle przechodzącym (1x) tła skalnego osadu z przykładowych próbek: E) 330,5–331 cm; F) 331–331,5 cm.

13. Tabele

Tabela 1. Wyniki datowania radiowęglowego rdzeni bocznych i uzupełniające rdzeni głównych osadów torfowisk Klakłowo i Kotoń. MKL – Laboratorium Datowań Bezwzględnych w Krakowie, we współpracy z Center For Applied Isotope Studies, University of Georgia, U.S.A. Kalibracja dat wykonana w programie OxCal v4.4.4 (Bronk Ramsey, 2021) przy użyciu krzywej kalibracyjnej IntCal20 (Reimer i in., 2020).

Nr	Głębokość próbki (cm)	Materiał organiczny do datowania	Kod próbki	Wiek ¹⁴ C (lat uncal BP)	Wiek skalibrowany 95.4% (lat cal BP)	Średnia	Sigma	Mediana
Rdzeń boczny Klakłowo B1								
1	65–67,5	Nasiona i owocki <i>Scirpus sylvaticus</i> (100), fragment igły <i>Larix decidua</i> (1), fragmenty igieł <i>Picea abies</i> (99), owocek <i>Ajuga reptans</i> (1), owocek <i>Carex rostrata</i> (1), pączki undiff. (1)	MKL-A7202	9057 ± 29	10 246–10 190	10 220	16	10 222
2	95–97,5	Owocki <i>Carex rostrata</i> (17), owocek <i>Carex nigra</i> (1), owocki <i>Betula</i> sect. <i>Albae</i> (17), łuski owocowe <i>Betula pubescens</i> (4), liścioślady (11), owocki <i>Filipendula ulmaria</i> (5), fragmenty igieł (8) i nasiono (1) <i>Larix decidua</i> , fragment nasiona (1) i fragmenty igieł (21) <i>Pinus sylvestris</i> , łuski pączkowe Coniferae (11)	MKL-A7203	9812 ± 30	11 258–11 194	11 225	18	11 226
3	145–147,5	Fragmenty igieł <i>Pinus sylvestris</i> (5), owocki (3) i epikarpy (2) <i>Carex rostrata</i> , nasiono (1) i fragmenty igieł (40) <i>Larix decidua</i> , pączki undiff. (4)	MKL-A7204	10 345 ± 35	12 466–11 953	12 208	148	12 181
4	170–172,5	Owocki (22) i łuski owocowe (2) <i>Betula</i> sect. <i>Albae</i> , fragmenty igieł <i>Larix decidua</i> (2), fragmenty igieł <i>Pinus sylvestris</i> , owocek <i>Valeriana</i>	MKL-A7215	10 866 ± 30	12 833–12 742	12 786	28	12 784

		<i>simplicifolia/dioica</i> (1), owocek <i>Urtica dioica</i> (1), fragmenty liści undiff. (1), pączki undiff. (5)						
5	195–197,5	Owocki <i>Betula</i> sect. <i>Albae</i> (23), owocki <i>Betula</i> sect. <i>Nanae</i> (1), fragmenty igieł <i>Pinus sylvestris</i> (14), łuski pączkowe Coniferae (2), liścioślady (7), pączki undiff. (2)	MKL-A7205	10 962 ± 32	12 985–12 759	12 863	55	12 862
6	220–222,5	Owocki <i>Carex diandra</i> (70), owocki (9) i epikarpy (2) <i>Carex rostrata</i> , owocki <i>Betula</i> sect. <i>Albae</i> (6), łuski owocowe <i>Betula</i> sp. (2), owocek Poaceae (1), fragmenty liści undiff. (1), łodyżki Bryopsida (5)	MKL-A7216	11 898 ± 34	13 987–13 605	13 741	81	13 759
7	235–237,5	Owocki (18), epikarpy (8) i owocki w epikarpach (5) <i>Carex rostrata</i> , owocek <i>Dryas octopetala</i> (1), owocki <i>Valeriana simplicifolia/dioica</i> (2)	MKL-A7206	12 162 ± 35	14 157–13 879	14 060	58	14 066

Rdzeń boczny Klakłowo B2

8	260–262,5	Owocki (3) i epikarpy <i>Carex rostrata</i> , łuski pączkowe Coniferae (7), owocki (7) i łuski owocowe (3) <i>Betula</i> sect. <i>Albae</i> (7), owocek (1) i łuska owocowa (1) <i>Betula</i> sect. <i>Nanae</i> , fragmenty liści undiff. (11), łodyżki Bryopsida (34)	MKL-A7207	12 733 ± 35	15 310–15 055	15 186	64	15 187
---	-----------	---	-----------	-------------	---------------	--------	----	--------

Rdzeń boczny Kotoń B1

9	50–52,5	Igły <i>Abies alba</i> (5), owocek <i>Rubus</i> sp. (1), fragment liści undiff. (23), owocki <i>Carex canescens</i> (5), nasiono <i>Scirpus sylvaticus</i> (1)	MKL-A7208	2192 ± 24	2310–2121	2222	58	2237
10	140–142,5	Fragmenty liści, nasiono (1) i fragmenty igieł (7) <i>Pinus sylvestris</i> , łuski pączkowe Coniferae (7), owocek (1) i łuski owocowe (3) <i>Betula pubescens</i> ,	MKL-A7209	11 039 ± 30	13 080–12 845	12 976	59	12 976

		owocki (8) i łuski owocowe (2) <i>Betula</i> sect. <i>Albae</i> , owocek <i>Carex diandra</i> (1)						
11	200–202,5	Owoc (1) <i>Betula</i> sect. <i>Albae</i> , nasiona <i>Stellaria</i> sp. (2), owocki (8) i nasiona (2) <i>Carex rostrata</i> , owocki <i>Carex diandra</i> (7), owocki <i>Carex nigra</i> (40)	MKL- A7210	11 767 ± 32	13 751–13 508	13 625	74	13 617
12	230–232,5	Owocki <i>Alchemilla</i> sp. (48), owocki <i>Ranunculus</i> <i>repens</i> (4), owocki <i>Carex magellanica</i> (20), owocki <i>Carex rostrata</i> (4), nasiona <i>Melandrium rubrum</i> (2)	MKL- A7211	12 164 ± 35	14 160–13 879	14 063	57	14 067
Rdzeń boczny Kotoń B2								
13	300–302,5	Owocki i epikarpy <i>Carex rostrata</i> (78), owoce <i>Carex diandra</i> (2), owocek <i>Betula</i> sect. <i>Albae</i> (1)	MKL- A7212	11 836 ± 32	13 781–13 601	13 687	54	13 687
14	300–302,5 (próbka powtórzona na innym materiale niż poprzednia)	Łodyżki Bryopsida (50)	MKL- A7217	11 490 ± 34	13 454–13 303	13 371	43	13 369
15	360–362,5	Owocki <i>Alchemilla</i> sp. (26), nasiona <i>Melandrium</i> <i>rubrum</i> (2), owocki <i>Urtica dioica</i> (2), owocki <i>Carex rostrata</i> (3), owocki <i>Carex magellanica</i> (3), owocek <i>Carex diandra</i> (1), owocek <i>Carex nigra</i> (1), owocek <i>Valeriana simplicifolia/dioica</i> (1), nasiona <i>Androsace</i> cf. <i>chamaejasme</i> (3), łodyżki Bryopsida	MKL- A7213	12 228 ± 33	14 309–14 051	14 144	86	14 127
16	330–332,5	Owoce (7) i epikarpy (11) <i>Carex rostrata</i> , owocki <i>Carex nigra</i> (3), owocek <i>Betula</i> sect. <i>Albae</i> (1), owocek <i>Alchemilla</i> sp. (3), owocek <i>Carex diandra</i> (1), pączki undiff. (1), łodyżki Bryopsida (20)	MKL- A7214	12 066 ± 32	14 041–13 817	13 930	70	13 918

Rdzeń główny Kotoń – dodatkowe próbki

17	215–217,5	Fragmenty liści undiff. (100), liście <i>Salix</i> sp. (5)	MKL-A7218	10 762 ± 31	12 756–12 713	12 735	11	12 735
18	125–127,5	Owocki (47) i epikarpy (40) <i>Carex rostrata</i>	MKL-A7219	9722 ± 29	11 232–10 902	11 162	60	11 180

Rdzeń główny Klakłowo – dodatkowe próbki

19	240 cm	Fragment drewna	MKL-A720	11 506 ± 33	13 456–13 311	13 382	41	13 382
----	--------	-----------------	----------	-------------	---------------	--------	----	--------

Tabela 2. Etapy paleoekologicznego rozwoju torfowisk osuwiskowych Klaklowo i Kotoń wydzielone w osadach rdzeni bocznych (Figura 3, 5, 7 i 9) w odniesieniu do rdzeni głównych (Figura 10 i 11).

Nr	Interwał głębokościowy i etap rozwoju paleoekologicznego (odpowiadający rdzeniowi głównemu)	Typ osadu i zespół makroszczałków roślin
Klaklowo – rdzeń boczny B1 (270–0 cm)		
1	270–267,5 cm KK-1	Wydzielenie to obejmuje osad pylasty z dużą domieszką frakcji piasku i drobnych fragmentów skał zupełnie pozbawiony makroszczałków roślin. Wydzielenie to może odpowiadać etapowi KK-1 głównego rdzenia osadów Klaklowa.
2	267,5–200 cm KK-2 i KK-3	Osady w tym interwale w dolnej części składają się z utworu pylastego z domieszką piasku, w górnej części zaś przechodzą w osady organiczne (torf). Zdominowane są przez makroszczałki roślinności torfowiskowej: <i>Carex rostrata</i> , <i>Carex diandra</i> i Bryopsida, oprócz których można zaobserwować też rzadsze wystąpienia <i>Melandrium rubrum</i> , <i>Juncus</i> sp., <i>Valeriana simplicifolia/dioica</i> , <i>Urtica dioica</i> , <i>Scirpus sylvaticus</i> lub <i>Phragmites australis</i> . Zaakcentowana jest też obecność makroszczałków organizmów wodnych, m.in. <i>Batrachium</i> sp., Ostracoda, <i>Daphnia</i> sp. W górnej części zony pojawiają się makroszczałki brzozy: <i>Betula</i> sect. <i>Nanae</i> oraz <i>Betula</i> sect. <i>Albae</i> (prawdopodobnie <i>Betula pubescens</i>) oraz pojedyncze łuski pączkowe Coniferae. Występowanie suchych siedlisk w otoczeniu zbiornika zaszyfrowane jest pojedynczym owockiem <i>Dryas octopetala</i> . Zapis makroszczałków tej zony można skorelować z etapami KK-2 i KK-3 głównego rdzenia osadów Klaklowa, które stanowią zapis sukcesji roślinności wodnej, torfowiskowej, po nich zaś lasu borealnego (brzoza) na stanowisku Klaklowo.
3	200–135 cm KK-4 i KK-5 (a i b)	W obrębie tego wydzielenia ma miejsce kontynuacja akumulacji torfu charakteryzującego się bardzo dużą zawartością makroszczałków drzew iglastych: <i>Pinus sylvestris</i> i <i>Larix decidua</i> , którym towarzyszą mniej liczne łuski pączkowe Coniferae. Zona charakteryzuje się również ciągłym, momentami licznym, występowaniem owocków i łusek <i>Betula</i> sect. <i>Albae</i> , prawdopodobnie <i>Betula pubescens</i> oraz mniej licznymi <i>Betula</i> sect. <i>Nanae</i> . Zidentyfikowano również liścioślady i pojedyncze fragmenty liści. Roślinność torfowiskowa jest reprezentowana jedynie przez pojedyncze owocki <i>Urtica dioica</i> , <i>Valeriana simplicifolia/dioica</i> , <i>Carex rostrata</i> i <i>Phragmites australis</i> . Pozostałe znaleziska obejmują liczne kokony larw Trichoptera oraz sporadyczne sklerotia <i>Cenococcum geophilum</i> . Interwał 200–135 cm zdaje się odpowiadać etapom KT-4 oraz KT-5 (a i b) głównego rdzenia osadów Klaklowa, które są typowe dla rozwoju torfowiska niskiego Klaklowo

(fazy wzrastającego i malejącego zawodnienia) w otoczeniu dobrze rozwiniętego lasu borealnego zdominowanego przez sosnę, modrzew i brzozę. Podczas gdy w centralnej części zbiornika (rdzeń główny) dochodziło do akumulacji torfów mszystych, w części brzeżnej torf składał się głównie z korzonków, tkanek, drewnienek i kory roślin naczyniowych, często mocno rozłożonych, a także detrytycznych fragmentów materii organicznej. Osad organiczny tego rodzaju wskazuje na dużo bardziej zmienne warunki zawodnienia i możliwe częste epizody przesuszenia i dostawy allochtonicznej materii organicznej.

- | | | |
|---|---------------------|--|
| 4 | 135–90 cm
KK-6 | W interwale tym następuje kontynuacja sedimentacji torfu, jednak zmienia się znacząco skład makroszczałków: prawie zupełnie zanikają igły i nasiona <i>Pinus sylvestris</i> i <i>Larix decidua</i> , mniej licznie reprezentowana jest też brzoza. Dopiero w stropowej części tej zony (100–90 cm), wymienione taksony występują na powrót liczniej, towarzyszą im zaś makroszczałki przede wszystkim <i>Carex rostrata</i> , <i>Carex nigra</i> , <i>Filipendula ulmaria</i> i liczne sklerotia <i>Cenococcum geophilum</i> . Wydzielenie to można skorelować z etapem KK-6 głównego rdzenia osadów torfowiska Klakłowo. |
| 5 | 90–50 cm
KK-7a | Interwał o zasięgu głębokościowym 90–50 cm charakteryzuje się zmianą sedimentacji z organicznej na minerogeniczną i od poprzedniej zony oddzielony jest hiatasem. Również w zespołach makroszczałków występuje bardzo duża zmiana: taksony drzew iglastych reprezentowane są prawie wyłącznie przez <i>Picea abies</i> , zaś oprócz świerka, grupa drzew i krzewów reprezentowana jest przez pojedyncze owoce <i>Sambucus racemosa</i> i <i>Rubus</i> sp. Po raz pierwszy pojawia się owocek <i>Ajuga reptans</i> . Jednak najliczniejszą grupę makroszczałków stanowią owocki i nasiona <i>Scirpus sylvaticus</i> (nasiona prawdopodobnie redeponowane do torfowiska) oraz sklerotia <i>Cenococcum geophilum</i> , potwierdzające allochtoniczny charakter osadów tej zony. Wykazuje ona duże podobieństwo do etapu KK-7 głównego rdzenia osadów torfowiska Klakłowo, a więc akumulację holocenijskiej pokrywy mineralnej na organicznych osadach torfowiska. |
| 6 | 50–12,5 cm
KK-7b | Wydzielenie to obejmuje wyższą część pokrywy minerogenicznej na torfach, o składzie makroszczałków reprezentowanym jedynie przez <i>Juncus</i> sp. i śladowe ilości nasion i owoców <i>Scirpus sylvaticus</i> . Odpowiada ono w dalszym ciągu etapowi KK-7 głównego rdzenia osadów torfowiska Klakłowo. |
| 7 | 12,5–0 cm
KK-8 | Ostatnie wydzielenie obejmuje współczesne osady organiczne torfowiska Klakłowo, zdominowane przez makroszczałki <i>Carex canescens</i> , <i>Scirpus sylvaticus</i> , <i>Juncus</i> sp., fragmenty liści i gemmule gąbek (Porifera), a także zawierające pojedyncze wystąpienia makroszczałków roślin siedlisk wilgotnych (<i>Lychnis flos-cuculi</i> , <i>Galeopsis tetrahit/pubescens</i> , <i>Urtica dioica</i>) oraz fragmenty igieł <i>Abies alba</i> . Wydzielenie to odpowiada etapowi KK-8 głównego rdzenia osadów torfowiska Klakłowo. |

Klakłowo – rdzeń boczny B2 (367,5–250 cm)

1	367,5–322,5 cm KK-1	Wydzielenie to obejmuje osad pylasty ze znaczącym udziałem frakcji piaszczystej i drobnych fragmentów skał. Na procesy redepozycji w otoczeniu zbiornika wskazuje też znaczna ilość szczątków <i>Cenococcum geophilum</i> występująca w spągowej części tych osadów. Na głębokości ok. 362,5–353 cm występuje wkładka organiczna zasobna w makroszczątki roślin (<i>Betula</i> sp., <i>Poa</i> cf. <i>chaixii</i> , <i>Stellaria nemorum</i> , <i>Urtica dioica</i>), powyżej której zarejestrowano prawie zupełny brak makroszczątków roślin, zaś licznie występują tu makroszczątki Ostracoda. Etap ten można zinterpretować jako rozwój zbiornika wodnego pozbawionego prawie w zupełności roślinności, z wyraźnym epizodem wypłykania i przekształcenia w krótkotrwałe torfowisko (wkładka organiczna). Etap ten odpowiada etapowi KK-1 rdzenia głównego, uwzględniając występowanie analogicznej wkładki organicznej w spągu rdzenia głównego.
2	322,5–312,5 cm KK-2	Osady w interwale 322,5–312,5 cm zawierają dużą liczbę oospor Characeae, kilka listków Bryopsida, pojedyncze nasiono <i>Juncus</i> sp. i fragmenty liści. Z uwagi na ubogi zasób makroszczątków, paleoekologiczna interpretacja tego etapu jest utrudniona, jednakże – przy wsparciu danych palinologicznych (przejście ze strefy pozbawionej pyłku do ubogiej w pyłek) - można spróbować skorelować go z etapem KK-2 rdzenia głównego.
3	312,5–250 cm KK-3	Na początku tego etapu można zaobserwować rozwój sukcesji roślinności wodnej (Characeae, <i>Batrachium</i> sp., <i>Potamogeton pusillus</i> , Ostracoda, <i>Daphnia</i> sp., Porifera i innych), zaś następnie również roślinności torfowiskowej (Bryopsida, <i>Carex rostrata</i>) wraz z ekspansją brzozy (<i>Betula</i> sect. <i>Albae</i> , <i>Betula pubescens</i> , <i>Betula</i> sect. <i>Nanae</i>) i drzew iglastych (Coniferae i <i>Larix decidua</i>). Przede wszystkim z uwagi na występowanie ogromnej liczby oosporów Characeae, etap ten może być on skorelowany z etapem KK-3 rdzenia głównego.

Kotoń – rdzeń boczny B1 (250–0 cm)

1	250–225 cm Od KT-1 do KT-3	Najniższe wydzielenie w profilu osadów rdzenia bocznego B1 z Kotonia obejmuje osady pylaste ze znaczną domieszką piasku i drobnego gruzu skalnego przechodzące w górnej części w osady organiczne. Wśród makroszczątków tej strefy dominują owocki <i>Alchemilla</i> sp., <i>Carex magellanica</i> , <i>Carex rostrata</i> , <i>Ranunculus repens</i> oraz nasiona <i>Melandrium rubrum</i> , wskazujące na rozwój płytkiego zarastającego zbiornika wodnego (<i>Potamogeton</i> sp., <i>Daphnia</i> sp.), przechodzącego w torfowisko niskie. Ponadto, pojedyncze nasiono <i>Androsace</i> cf. <i>chamaejasme</i> sugeruje otoczenie zbiornika o charakterze stepo-tundry, stąd też można ten interwał skorelować z etapami od KT-1 do KT-3 głównego rdzenia osadów Kotonia (niemożliwe do rozdzielenia w rdzeniu bocznym Kotoń B1).
2	225–185 cm KT-4	Interwał ten obejmuje torfy utworzone głównie z tkanek i korzonków roślin naczyniowych, jedynie miejscami mające charakter torfów mszystych. Dobrze zachowane łądźki Bryopsida występują tylko w części tej strefy. Roślinność torfowiskowa reprezentowana jest również przez liczne makroszczątki <i>Carex nigra</i> , <i>Carex diandra</i> i podrzędnie <i>Carex rostrata</i> . <i>Alchemilla</i> sp. zanika w tej strefie, w jednej z próbek zaś pojawiają się nasiona <i>Stellaria</i> sp. Na suchsze siedliska

w otoczeniu torfowiska wskazuje pojedyncze występowanie *Picris hieracioides*. W sąsiedztwie torfowiska pojawiają się również drzewa: brzoza (*Betula* sect. *Albae*) oraz sosna (*Pinus sylvestris*). Wydzielenie to w przybliżeniu odpowiada etapowi KT-4 głównego rdzenia osadów Kotonia.

- | | | |
|---|-----------------------------|--|
| 3 | 185–140 cm
KT-5a | W interwale tym kontynuowana jest akumulacja torfu, który miejscami wykazuje ślady rozkładu i przesuszenia. W składzie makroszczałkowym nadal występują owocki i łuski <i>Betula</i> sect. <i>Albae</i> oraz pojedyncze makroszczałki Coniferae i <i>Pinus sylvestris</i> , sygnalizujące dalszy rozwój lasu borealnego w otoczeniu torfowiska. Na występowanie mniej zawodnionych warunków środowiska sedymentacyjnego może wskazywać spadek liczby makroszczałków <i>Carex diandra</i> i <i>Carex nigra</i> oraz wycofanie się Bryopsida. Dlatego też, wydzielenie to wykazuje podobieństwo do etapu KT-5a głównego rdzenia osadów torfowiska Kotoń. Ponadto, w najwyższej próbce należącej do tej strefy (głębokość 140–142,5 cm), można zaobserwować bardzo liczne fragmenty liści oraz makroszczałki brzozy i sosny, zaś interwał powyżej (140–130 cm) składa się wyłącznie z dużych fragmentów drewna. |
| 4 | 130–95 cm
KT-5b | Wydzielenie to stanowi zapis prawie całkowitego zaniku makroszczałków drzew i krzewów (jedynie pojedyncze występowanie owoców <i>Betula</i> sect. <i>Albae</i>) oraz – głównie w dolnej części - zawiera nieliczne makroszczałki roślinności torfowiskowej (<i>Carex diandra</i> , <i>Carex nigra</i> , <i>Carex rostrata</i> , <i>Valeriana simplicifolia/dioica</i>). W górnej części, wraz ze zmianą akumulacji torfu na osady minerogeniczne, brak jest prawie zupełnie makroszczałków roślin. Interwał ten można zestawiać z etapem KT-5b głównego rdzenia osadów torfowiska Kotoń. |
| 5 | 95–55 cm
Od KT-6 do KT-8 | Wydzielenie to obejmuje osady pokrywy mineralnej zawierającej liczne nasiona <i>Scirpus sylvaticus</i> i sklerotia <i>Cenococcum geophilum</i> , które potwierdzają występowanie intensywnej redepozycji materiału z otoczenia torfowiska. Interwał ten może odpowiadać etapom od KT-6 do KT-8 głównego rdzenia osadów torfowiska Kotoń (niemożliwe do rozdzielania w rdzeniu bocznym Kotoń B1). |
| 6 | 55–15 cm
KT-8 | W interwale tym ma miejsce kontynuacja sedymentacji pokrywy minerogenicznej, jednakże oddzielony jest od dolnej części pokrywy hiatusem. Zespół makroszczałków reprezentowany jest w dalszym ciągu przez liczne sklerotia <i>Cenococcum geophilum</i> i występujące licznie jedynie w najwyższej próbce tej strefy makroszczałki <i>Scirpus sylvaticus</i> . Grupa drzew, krzewów i krzewinek zdominowana jest przez fragmenty igieł <i>Abies alba</i> i <i>Picea abies</i> oraz owocki <i>Sambucus racemosa</i> , <i>Rubus</i> sp. i fragmenty liści. Pojedynczo pojawiają się owocki <i>Ranunculus repens</i> . Ponadto, w najwyższej próbce tego interwału (20–22,5 cm) licznie występują nasiona <i>Juncus</i> sp. i fragmenty makro-węgla. Wydzielenie to koresponduje z etapem KT-8 głównego rdzenia osadów torfowiska Kotoń. |
| 7 | 15–0 cm
KT-9 | Ostatnie wydzielenie w profilu osadów rdzenia bocznego Kotoń B1 stanowi zapis osadów współczesnego torfowiska, w których zidentyfikowano liczne makroszczałki <i>Carex canescens</i> , <i>Carex</i> cf. <i>flava</i> oraz <i>Potentilla</i> cf. <i>alba</i> . Interwał ten odpowiada etapowi KT-9 głównego rdzenia osadów torfowiska Kotoń. |

Kotoń – rdzeń boczny B2 (400–300 cm)

1	400–372,5 cm KT-1	Wydzielenie to charakteryzuje się występowaniem osadu pylastego ze znaczącym udziałem frakcji piaszczystej i drobnych fragmentów skał oraz prawie zupełnym brakiem makroszczątków roślin (poza pojedynczym owocem <i>Alchemilla</i> sp. i kokonem larwy Trichoptera). Wydzielenie to można zinterpretować jako niezasiedlony zbiornik wodny odpowiadający etapowi KT-1 rdzenia głównego Kotonia.
2	372,5–340 cm KT-2	Etap ten można zinterpretować jako rozwój zbiornika wodnego z sukcesją roślinności wodnej (Characeae, <i>Batrachium</i> sp., <i>Potamogeton alpinus</i> , Ostracoda, <i>Daphnia</i> sp., <i>Simocephalus</i> sp. i innych) i torfowiskowej (Bryopsida oraz owocki <i>Alchemilla</i> sp., podrzędnie zaś owocki i epikarpy <i>Carex nigra</i> , <i>Carex rostrata</i> , <i>Carex magellanica</i> i <i>Carex diandra</i> oraz owocki <i>Valeriana simplicifolia/dioica</i>), w którym zachodziła akumulacja mułku organicznego (gytia). Zbiornik ten był otoczony siedliskami suchymi, na przykład stepo-tundrą (<i>Androsace</i> cf. <i>chamaejasme</i>) zaś jego występowanie odpowiada etapowi KT-2 rdzenia głównego Kotonia.
3	340–320 cm KT-3	Wydzielenie 340–320 cm jest etapem przejściowym pomiędzy zbiornikiem wodnym (wciąż obecne makroszczałki np. <i>Batrachium</i> sp. i <i>Potamogeton alpinus</i>) a torfowiskiem (np. Bryopsida, <i>Carex rostrata</i> , <i>Carex diandra</i>), w którego otoczeniu siedliska suche (cf. <i>Dryas octopetala</i>), świeże i wilgotne (<i>Picris hieracioides</i> i <i>Heracleum sphondylium</i>) są zastępowane lasem borealnym (<i>Betula</i> sect. <i>Albae</i>). Etap ten może być skorelowany z etapem KT-3 rdzenia głównego.
4	320–300 cm KT-4	Wzrastający udział fragmentów łodyżek Bryopsida oraz makroszczałków <i>Carex rostrata</i> i <i>Menyanthes trifoliata</i> oraz brak makroszczałków organizmów wodnych wskazuje na przekształcenie lokalnego siedliska w torfowisko niskie z akumulacją torfu mszystego. W otoczeniu torfowiska prawdopodobnie następowała ekspansja lasu borealnego i zanik stepo-tundry (brak makroszczałków roślin reprezentujących suche siedliska). Etap ten może być skorelowany z wydzieleniem KT-4 rdzenia głównego Kotonia.

Tabela 3. Daty erupcji Vedde Ash, Laacher See Tephra, Neapolitan Yellow Tuff oraz Sfinta Ana na podstawie danych literaturowych (zobacz Bronk Ramsey i in., 2015 - Vedde Ash, LST, NYT; Juvigné i in., 1994 - Sfinta Ana); daty przyjęte w oparciu o zaktualizowane (z użyciem najnowszych dostępnych metod oraz radiowęglowych krzywych kalibracyjnych: IntCal13 i Marine13) oszacowania wieku tych erupcji (rekomendowany model 2, Bronk Ramsey i in., 2015) oraz odpowiadające zakresom czasowym erupcji przedziały głębokości w sekwencji osadów torfowisk Kotoń i Klakłowo (wytypowane w oparciu o modele wiek-głębokość), z których pobrano próbki do analizy. * - zobacz wyjaśnienie w Bronk Ramsey i in., 2015.

Horyzont tefry	Data erupcji na podstawie literatury ($\mu \pm \sigma$ lat cal BP)	Zaktualizowane oszacowania wieku erupcji (model 2)		Klakłowo		Kotoń	
		95% zakres prawdopodobieństwa (lat cal BP)	$\mu \pm \sigma$ (lat cal BP)	Przedział głębokości rdzenia głównego (cm)	Miąższość (cm)	Przedział głębokości rdzenia głównego (cm)	Miąższość (cm)
Vedde Ash	12 121 \pm 1 [57]* 12 066 \pm 42	12 102–11 914	12 023 \pm 43		Nie analizowane		
Laacher See Tephra (LST)	12 880 \pm 40	12 979–12 889	12 937 \pm 23	190–201	11	248–254	6
Neapolitan Yellow Tuff (NYT)	14 190 \pm 680	14 588–13 884	14 194 \pm 172	309–359	50	363–495	132
Sfinta Ana	10 700 \pm 180 lat uncal BP	-	-		Nie analizowane		

14. Załączniki

14.1. Publikacja 1 – Tytuł

Pilch, J., Margielewski, W., Stachowicz-Rybka, R., Buczek, K., Obidowicz, A., Korzeń, K., 202x. Effect of topographic position on differential biotic and lithological responses to the late glacial–early Holocene climatic oscillations recorded in sediments of two landslide fens (the Outer Western Carpathians, S Poland). (Artykuł na etapie recenzji w czasopiśmie *The Holocene*).

MNISW (2024 rok): 140 pkt.

IF: (5-letni) 2,2; (2024 rok) 1,8

14.2. Publikacja 1 – Oświadczenia współautorów

Kraków, 20.10.2025

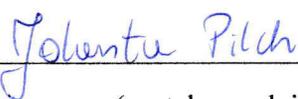
Mgr inż. Jolanta Pilch
Instytut Ochrony Przyrody
Polskiej Akademii Nauk
al. Adama Mickiewicza 33,
31-120 Kraków

OŚWIADCZENIE

Oświadczam, że w pracy:

Pilch, J., Margielewski, W., Stachowicz-Rybka, R., Buczek, K., Obidowicz, A., Korzeń, K., 202x.
Effect of topographic position on differential biotic and lithological responses to the late glacial–early
Holocene climatic oscillations recorded in sediments of two landslide fens (the Outer Western
Carpathians, S Poland). (Artykuł na etapie recenzji w czasopiśmie The Holocene).

mój udział polegał na: wykonaniu prac w terenie, poborze próbek, analizie makroszczątków roślin,
opracowaniu (statystycznym i graficznym) danych: makroszczątkowych, strat prażenia,
palinologicznych, datowań radiowęglowych (w tym przygotowaniu modelu wiek-głębokość),
przeprowadzeniu interpretacji paleośrodowiska oraz przygotowaniu manuskryptu (draft oraz
redagowanie). Mój udział w pracach wynosi 90%.



(czytelny podpis współautora)

Kraków, 20.10.2025

Dr hab. inż Włodzimierz Margielewski, prof. IOP PAN
Instytut Ochrony Przyrody
Polskiej Akademii Nauk
al. Adama Mickiewicza 33,
31-120 Kraków

O Ś W I A D C Z E N I E

Oświadczam, że w pracy:

Pilch, J., **Margielewski, W.**, Stachowicz-Rybka, R., Buczek, K., Obidowicz, A., Korzeń, K., 202x. Effect of topographic position on differential biotic and lithological responses to the late glacial–early Holocene climatic oscillations recorded in sediments of two landslide fens (the Outer Western Carpathians, S Poland). (Artykuł na etapie recenzji w czasopiśmie The Holocene).

mój udział polegał na: pomocy w wykonaniu prac w terenie, konceptualizacji, nadzorze, pomocy w interpretacji paleośrodowiskowej i przygotowaniu manuskryptu (recenzja i redagowanie). Mój udział w pracach wynosi 3,5%.



(czytelny podpis współautora)

Kraków, 20.10.2025

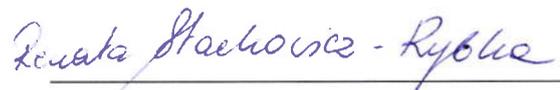
Dr hab. Renata Stachowicz Rybka, prof. IB PAN
Instytut Botaniki im. W. Szafera
Polskiej Akademii Nauk
ul. Lubicz 46,
31-512 Kraków

OŚWIADCZENIE

Oświadczam, że w pracy:

Pilch, J., Margielewski, W., **Stachowicz-Rybka, R.**, Buczek, K., Obidowicz, A., Korzeń, K., 202x.
Effect of topographic position on differential biotic and lithological responses to the late glacial–early
Holocene climatic oscillations recorded in sediments of two landslide fens (the Outer Western
Carpathians, S Poland). (Artykuł na etapie recenzji w czasopiśmie The Holocene).

mój udział polegał na: pomocy w przeprowadzeniu analizy makroszczątków roślin, conceptualizacji,
nadzorze, pomocy w interpretacji paleośrodowiskowej i przygotowaniu manuskryptu (recenzja i
redagowanie). Mój udział w pracach wynosi 3,5%.



(czytelny podpis współautora)

Kraków, 20.10.2025

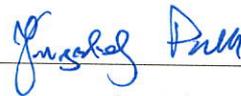
Dr Krzysztof Buczek
Instytut Ochrony Przyrody
Polskiej Akademii Nauk
al. Adama Mickiewicza 33,
31-120 Kraków

O Ś W I A D C Z E N I E

Oświadczam, że w pracy:

Pilch, J., Margielewski, W., Stachowicz-Rybka, R., **Buczek, K.**, Obidowicz, A., Korzeń, K., 202x. Effect of topographic position on differential biotic and lithological responses to the late glacial–early Holocene climatic oscillations recorded in sediments of two landslide fans (the Outer Western Carpathians, S Poland). (Artykuł na etapie recenzji w czasopiśmie The Holocene).

mój udział polegał na: pomocy w wykonaniu prac w terenie, konceptualizacji, pomocy w opracowaniu graficznym danych, interpretacji paleośrodowiskowej, opracowaniu modelu wiek-głębokość oraz przygotowaniu manuskryptu (recenzja i redagowanie). Mój udział w pracach wynosi 1%.



(czytelny podpis współautora)

Kraków, 20.10.2025

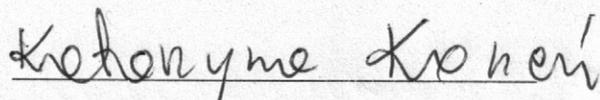
Dr Katarzyna Korzeń
ul. Kazimierza Wielkiego 110/3-4,
30-082 Kraków

OŚWIADCZENIE

Oświadczam, że w pracy:

Pilch, J., Margielewski, W., Stachowicz-Rybka, R., Buczek, K., Obidowicz, A., **Korzeń, K.**, 202x.
Effect of topographic position on differential biotic and lithological responses to the late glacial–early
Holocene climatic oscillations recorded in sediments of two landslide fans (the Outer Western
Carpathians, S Poland). (Artykuł na etapie recenzji w czasopiśmie The Holocene).

mój udział polegał na: wykonaniu analizy palinologicznej i palinomorf niepyłkowych (NPPs) oraz
pomocy w przeprowadzeniu interpretacji paleośrodowiska i przygotowaniu manuskryptu (recenzja i
redagowanie). Mój udział w pracach wynosi 1%.


(czytelny podpis współautora)

14.3. Publikacja 1

Effect of topographic position on differential biotic and lithological responses to the late glacial–early Holocene climatic oscillations recorded in sediments of two landslide fens (the Outer Western Carpathians, S Poland)

Journal:	<i>The Holocene</i>
Manuscript ID	Draft
Manuscript Type:	Paper
Date Submitted by the Author:	n/a
Complete List of Authors:	Pilch, Jolanta; Institute of Nature Conservation Polish Academy of Sciences Margielewski, Włodzimierz; Institute of Nature Conservation Polish Academy of Sciences Stachowicz-Rybka, Renata; W Szafer Institute of Botany Polish Academy of Sciences Buczek, Krzysztof; Institute of Nature Conservation Polish Academy of Sciences Obidowicz, Andrzej; W Szafer Institute of Botany Polish Academy of Sciences Korzeń, Katarzyna; Kazimierza Wielkiego 110/3-4
Keywords:	Altitude and exposure influence, multi-proxy analysis, plant macrofossil analysis, radiocarbon absolute chronology, landslide, early Holocene, late glacial, Preboreal, Younger Dryas, Greenland ice cores, correlation
Abstract:	Landslide fens are characteristic landforms of the Beskid Makowski Mountains area in the Outer Western Carpathians (S Poland) and contain rarely occurring late glacial and Holocene organic-minerogenic sedimentary sequences. Multi-proxy study (radiocarbon dating, loss on ignition, plant macrofossil and pollen analyses) was applied to verify whether the late glacial-early Holocene climatic and palaeoenvironmental changes were recorded differently between two sites varying in topographic position within the same mountain massif: the Kotoń landslide fen characterized by the southern exposure and near-ridge position and the Klakłowo landslide fen characterized by the northern exposure and mid-slope position. Results revealed that the responses of biotic and lithological proxies to the climatic phases differs between the Klakłowo and Kotoń landslide fens mostly in relation to the smaller-scale climatic oscillations. The characteristics of the Klakłowo fen catchment, including area, shape, relief, bedrock geology and specific local landforms, could contribute to the much more pronounced signal of the GI-1b/Gerzensee oscillation and Preboreal oscillation at this site than in the Kotoń site. Expansion and/or decline of the dominating vegetation taxa (<i>Pinus</i> , <i>Betula</i> sect. <i>Albae</i> , <i>Carex</i> , <i>Bryopsida</i>) and changes in minerogenic matter delivery induced by the global-scale climatic reversals: GI-1a–c /Allerød, GS-1/Younger Dryas and Holocene, occur

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

	approximately at the same time in both Klaklowo and Kotoń landslide fens and show no striking dependency on exposure or elevation. An exception is the longer survival of <i>Larix decidua</i> , <i>Pinus sylvestris</i> and <i>Coniferae</i> during the early Holocene at the Klaklowo site, probably facilitated by its northern exposure and diversified landslide relief.



1 **Abstract**

2 Landslide fens are characteristic landforms of the Beskid Makowski Mountains area in the
3 Outer Western Carpathians (S Poland) and contain rarely occurring late glacial and Holocene
4 organic-minerogenic sedimentary sequences. Multi-proxy study (radiocarbon dating, loss on
5 ignition, plant macrofossil and pollen analyses) was applied to verify whether the late glacial-
6 early Holocene climatic and palaeoenvironmental changes were recorded differently between
7 two sites varying in topographic position within the same mountain massif: the Kotoń
8 landslide fen characterized by the southern exposure and near-ridge position and the
9 Klaklowo landslide fen characterized by the northern exposure and mid-slope position.
10 Results revealed that the responses of biotic and lithological proxies to the climatic phases
11 differs between the Klaklowo and Kotoń landslide fens mostly in relation to the smaller-scale
12 climatic oscillations. The characteristics of the Klaklowo fen catchment, including area,
13 shape, relief, bedrock geology and specific local landforms, could contribute to the much
14 more pronounced signal of the GI-1b/Gerzensee oscillation and Preboreal oscillation at this
15 site than in the Kotoń site. Expansion and/or decline of the dominating vegetation taxa (*Pinus*,
16 *Betula sect. Albae*, *Carex*, Bryopsida) and changes in minerogenic matter delivery induced by
17 the global-scale climatic reversals: GI-1a–c /Allerød, GS-1/Younger Dryas and Holocene,
18 occur approximately at the same time in both Klaklowo and Kotoń landslide fens and show no
19 striking dependency on exposure or elevation. An exception is the longer survival of *Larix*
20 *decidua*, *Pinus sylvestris* and Coniferae during the early Holocene at the Klaklowo site,
21 probably facilitated by its northern exposure and diversified landslide relief.

22 **Keywords:**

23 Altitude and exposure influence, multi-proxy analysis, plant macrofossil analysis, radiocarbon
24 absolute chronology, landslide, early Holocene, late glacial, Preboreal, Younger Dryas,
25 Greenland ice cores, correlation

Introduction

Landslide fens are a type of mountain minerogenic mires which develop within the landslide depressions and are characterized by a greater amount of precipitation (variable hydrological regime) and a greater dynamics of minerogenic sediment supply than typical lowland mires (Margielewski, 2014, 2018). Sediments accumulated in landslide mires and lakes sensitively record past changes of environment, including the influence of regional climatic factors, impact of the local features (e.g. hydrological conditions, availability of minerogenic material, topography of the fen sedimentary basin) and human activity. Landslide fens combine features of both lake-fen and the slope sedimentary environments (Margielewski, 2014, 2018). Landslide fens are characteristic landforms of the Beskid Makowski Mountains area, in the Outer Western Carpathians, occurring in several locations and containing rare late glacial and Holocene sediments of great thicknesses (Margielewski et al., 2022b). Two sites are particularly interesting, the Kotoń and Klakłowo landslide fens, possessing 5.0 and 3.7 m of organic-minerogenic sediment sequences, respectively. Due to their differentiated topographic positions within the same mountain massif, they provide an excellent opportunity for correlating profiles and tracking the impact of regional and local environmental factors, including altitude, exposure and catchment characteristics, on the lithological and biotic records.

The influence of the local geomorphological environment on the late glacial and early Holocene palaeo-records of mountain lakes and mires (including landslide fens) in the Western Carpathians was studied in details in a scale of single localities (Margielewski et al., 2010; Pánek et al., 2010; Šímová et al., 2019) as well as it was reviewed within a comprehensive regional compilations (Kłapyta et al., 2016; Margielewski, 2006, 2014, 2018). Although the regional correlations of mountainous lake and mire deposits (also transects across sites) concern mostly biotic and climatic changes, e.g. treeline and timberline shifts,

1
2
3 refugial role of a site, age of deglaciation, frequently also the impact of altitude and exposure
4
5 on these phenomena is explored. Such studies were carried out for the Tatra Mountains
6
7 (Kłapyta et al., 2016), the Romanian Carpathians and the adjacent regions (Feurdean et al.,
8
9 2007, 2016; Magyari, 2002) or for the Alps and neighbouring regions (Ammann et al., 2000,
10
11 2014; David, 1993; Lotter et al., 1992). The local comparisons of lakes/mires deposits situated
12
13 closely to each other in the mountainous areas are less frequent (Feurdean and Bennike, 2004)
14
15 and sometimes, despite the proximity, similar elevation and aspect, they reveal prominently
16
17 various vegetation history (Michczyński et al., 2013). Correlations between sites located
18
19 within one mountain massif but with different exposure and altitude (Magyari et al., 2018)
20
21 and/or different catchment characteristics (Hubay et al., 2018; Rubensdotter and Rosqvist,
22
23 2003) are also less common.
24
25
26
27

28
29 Earlier studies in the Kotoń and Klakłowo landslide fens were conducted by
30
31 Margielewski (2001a, 2001b) and Margielewski et al. (2003), however, the absence of
32
33 continuous absolute chronology (age-depth model) based on AMS radiocarbon dates did not
34
35 allow to assign to the pollen-based chronozones' boundaries the precise calibrated
36
37 radiocarbon age. Furthermore, these earlier investigations of both sites focused more on the
38
39 late Holocene sequence, leaving the late glacial-early Holocene sediment sequence
40
41 unexplored in details. The lack of defined timeframes for the older palynologically-
42
43 determined stratigraphic divisions is frequent in the Carpathians and its foreland (Harmata,
44
45 1987; Koperowa, 1961; Mamakowa, 1962; Ralska-Jasiewiczowa, 1980), yet recently the
46
47 significance of accurate calibrated age scale for the late glacial/Holocene pollen records in
48
49 this region was recognized and addressed (Margielewski et al., 2022a; Michczyński et al.,
50
51 2013). Furthermore, in the situation of the absence of the terrestrial late glacial-Holocene
52
53 stratotype for the Outer Western Carpathians region, INTIMATE event stratigraphy based on
54
55 the Greenland ice core oxygen isotope record can be used as the extraregional absolute
56
57
58
59
60

1
2
3 chronology for correlation (Björck et al., 1998; Lowe et al., 2008; Rasmussen et al., 2014).
4
5 Such attempt has been recently undertaken to investigate the oldest minerogenic sections of
6
7 the Kotoń and Klaklowo landslide fen deposits (Bølling-Older Dryas-beginning of Allerød)
8
9 using high-resolution multi-proxy methods and correlation to Greenland ice cores event
10
11 stratigraphy (Pilch et al., 2025a, 2025b). The current study focuses on the younger climatic
12
13 oscillations: GI-1a–c/Allerød, GS-1/Younger Dryas, Preboreal phase and the Preboreal/Boreal
14
15 phase (from ca. 13,900 to ca. 10,000 cal BP).
16
17

18
19 The goal of the study presented in this paper is to verify whether the late glacial and
20
21 early Holocene climatic and palaeoenvironmental changes were recorded differently between
22
23 the Kotoń landslide fen characterized by the southern exposure and near-ridge position and
24
25 the Klaklowo landslide fen characterized by the northern exposure and mid-slope position.
26
27 Local palaeoecological development of the Kotoń and Klaklowo fens was reconstructed based
28
29 on multi-proxy analysis: radiocarbon dating, loss on ignition, plant macrofossil and pollen
30
31 analyses. To trace the regional and mountain-scale vegetation changes, the local establishment
32
33 and recession times of a few representative species/plants group were determined using the
34
35 results of the plant macrofossil analysis with support of the pollen data (Ammann et al.,
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
2014).

Site description

[insert Figure 1]

Location, geology and geomorphology

According to physico-geographical division of Poland, the study area is situated in the mesoregion of Beskid Makowski Mountains, which is part of the subprovince of the Outer Western Carpathians in the south of Poland (Solon et al., 2018) (Figure 1 A, B and C). The Outer Carpathians are composed of flysch rocks (siliciclastic-clayey turbidites and

1
2
3 occasionally also carbonate and siliceous rocks) which age of formation spans from Late
4 Jurassic to Early Miocene (Książkiewicz, 1972). Study area is located within the Siary
5 Subunit which belongs to the Magura Unit, being one of the overthrust tectonic units of the
6 Outer Western Carpathians (Książkiewicz et al., 2016). Kotoń and Klakłowo landslide fens
7 are embedded within the slopes of the Mt. Koskowa Góra range, beneath the ridge
8 culminations of Mt. Kotoń (857 m a.s.l.) and Mt. Pękałówka (839 m a.s.l.), respectively
9 (Figure 1 C, D and E). Kotoń site has altitude of 739 m a.s.l., southern exposure and near-
10 ridge position above the springs of the Rusnaków stream, being the left tributary of the
11 Krzczonówka stream (Figure 1 D and E). Klakłowo site has altitude of 466 m a.s.l., northern
12 exposure, mid-slope position and it is opening toward the valley of one of the Raba river
13 tributaries (Figure 1 D and E). The distance between the sites equals ca. 1900 m, altitude
14 difference: 273 m.

Climate

33
34
35 Based on measurements from years 1991–2021 (Climate Data, 2024), the climate of Zawadka
36 and Stróża villages (located beneath the Kotoń and Klakłowo landslides, respectively) is
37 warm temperate with a considerable amount of precipitation, affected by rough mountainous
38 terrain. The mean annual temperature is 7.9°C and mean annual sum of precipitation is 1063
39 mm. In the region of the Beskid Makowski Mountains, spring is long, cold and rainy, whereas
40 autumn is also long but dry, with frequent temperature oscillations. Similarly to the adjacent
41 regions, temperature inversions tend to occur in river valleys (additional information on
42 climate in Supplemental Material).

Landslides description

1
2
3 The Kotoń landslide developed exclusively in the thick-bedded Magura sandstones (which
4 build most of the Mt. Koskowa Góra range) and has a shape of a vast wedge with two linear
5 head scarps, between which a flattening of the landslide body occurs (Figure 1 F, G and I).
6
7

8
9
10 The Klaklowo landslide zone possesses an amphitheatre shape (Figure 1 H and J). The
11 bedrock in the area of the semi-circular head scarp and sub-scarp depression (Klaklowo fen)
12 consists of flysch rocks of the Eocene age (Książkiewicz et al. 2016): shales, green shales and
13 thin-bedded sandstones of Hieroglyphic beds, variegated shales and thick-bedded sandstones
14 and conglomerates and shales of Lower Pasierbiec Sandstones and Osielec Sandstones
15 (Figure 1 F). The area above the landslide, similarly to the Kotoń site, is built of the
16 sandstones of the Magura beds (additional information on landslides in Supplemental
17 Material).
18
19
20
21
22
23
24
25
26
27
28
29
30

31 *Landslides' sub-scarp depressions, hydrology and fen deposits*

32
33 In case of the Kotoń landslide, the longitudinal sub-scarp depression (ca. 40 m wide and ca.
34 90 m long) developed along the foot of the western head scarp (Figure 1 G, I, K, M and N).
35 From the east it is dammed by colluvial rampart what resulted in minerogenic mire (a fen)
36 development and filling the depression with up to 5 m of late glacial and Holocene organic-
37 minerogenic sediments. Presently, except for the Rusnaków stream emerging in the lower part
38 of the Kotoń landslide, there are no permanent streams flowing down from the head scarp and
39 slopes to the sub-scarp depression, although the temporary ones are probable (Figure 1 G and
40 I).
41
42
43
44
45
46
47
48
49

50
51 In case of the Klaklowo landslide, the sub-scarp depression (ca. 40 m wide and ca. 100 m
52 long) has a shape slightly curved southward because of the semicircular main scarp of the
53 landslide bordering it from the south (Figure 1 H, J, L, O and P). From the north, the
54 depression is surrounded by colluvial rampart, having an outlet on the eastern side through
55
56
57
58
59
60

1
2
3 which a permanent stream is flowing out into the valley. Nowadays, the Klaklowo landslide's
4 sub-scarp depression is occupied by a minerogenic mire (a fen) filled with up to 3.7 m of late
5 glacial and Holocene organic-minerogenic sediments. On the opposite site to the stream
6
7
8
9
10 (draining the fen through the outlet in colluvial dam), the Klaklowo mire is fed by a few small
11
12
13 (permanent and periodical) watercourses flowing down from the head scarp to the sub-scarp
14
15 depression.

16 17 18 19 ***Soil and vegetation***

20
21 Nowadays, slopes of the Beskid Makowski Mountains are covered predominantly with brown
22
23 soils (Bank Danych o Lasach, 2025). Duration of the mean annual growing season ranges
24
25 between 220 and 230 days (Tomczyk and Bednorz, 2022). In the direct vicinity of the Kotoń
26
27 and Klaklowo fens the surrounding slopes and landslide landforms are forested (the
28
29 Carpathian beech forest, Figure 1 M, N, O and P) predominately by fir (*Abies alba*) and beech
30
31 (*Fagus sylvatica*) with some presence of spruce (*Picea* sp.). Birch (*Betula* sp.), poplar
32
33 (*Populus* sp.) and larch (*Larix* sp.) occur locally around the fens, whereas willow (*Salix* sp.)
34
35 shrubs grow also within the mires' borders. Some parts of the wet margins of streams around
36
37 Klaklowo are covered by alder (*Alnus* sp.) (additional information on vegetation in
38
39 Supplemental Material).
40
41
42
43
44
45
46

47 **Materials and methods**

48 49 ***Coring, sampling and calculations of additional parameters***

50
51 Sediment cores were taken using INSTORF Russian peat sampler (diameter: 8 cm) from the
52
53 mires developed in the sub-scarp depressions of the Kotoń (49°46'5.12"N; 19°54'12.96"E, 739
54
55 m a.s.l., Figure 1 I and K,) and Klaklowo (N 49° 46.772'; E 19° 55.383'; 466 m a.s.l., Figure
56
57 1 J and L) landslides at sites where thickness of deposits was the greatest: 500 and 367 cm,
58
59
60

1
2
3 respectively. Subsequently, the cores were divided into sediment samples which underwent
4
5 loss on ignition, plant macrofossil and pollen analyses and radiocarbon dating. For the
6
7 purpose of this study (comparison of the long-lasting fen stages between both sites during the
8
9 late glacial and early Holocene), the corresponding depth sections, ca. 370–100 cm for the
10
11 Kotoń and ca. 310–70 cm for the Klaklowo sites (ca. 13,900 to ca. 10,000 cal BP) were
12
13 selected. The results of the multi-proxy analyses of the deepest sections of the Kotoń and
14
15 Klaklowo mires (500–300 and 367–250 cm, respectively) encompassing climatic oscillations
16
17 of Bølling-Older Dryas-beginning of Allerød, were presented in the earlier papers (Pilch et
18
19 al., 2025a; 2025b). The results presented in this paper overlap with the data presented in those
20
21 papers only within the beginning of the Allerød deposits.
22
23
24
25

26 All maps and cross-sections presenting localization of the study area (Figure 1) were
27
28 composed in QGIS 3.22.10 (QGIS Development Team, 2021). To better understand and
29
30 explain the similarities and differences between palaeo-records of the Kotoń and Klaklowo
31
32 fens, additional parameters characterizing the physical environment of the sites were
33
34 calculated: solar irradiation and catchment area. The calculations were done using GRASS
35
36 GIS algorithms (GRASS Development Team, 2015) and the detail methodology and results of
37
38 these calculations are given in the Supplemental Material and are referred to in the Discussion
39
40 section.
41
42
43
44
45
46

47 ***Radiocarbon dating and age-depth models***

48
49 Material for radiocarbon dating (Acceleration Mass Spectrometry, AMS) was obtained
50
51 simultaneously with plant macrofossil analysis of the Klaklowo and Kotoń sediment samples
52
53 from the depth sections of 367–68 cm and 440–77 cm, respectively (see context of dating,
54
55 Table 1) and included plant fruits, seeds, leaves, needles and stems of mosses (Table 1).
56
57 Eighteen radiocarbon dates were acquired in total: 12 for the Klaklowo fen and 6 for the
58
59
60

1
2
3 Kotoń fen deposits, and they were subsequently calibrated in the OxCal v. 4.4.4 software
4
5 (Bronk Ramsey 2009, 2021) using the IntCal20 calibration curve (Reimer et al. 2020), to
6
7 standardize the calibrated results.
8
9

10 Absolute chronologies were determined for the Klaklowo and Kotoń sediment
11
12 sequences, based on ten ^{14}C AMS and six ^{14}C AMS dates by constructing the Bayesian age-
13
14 depth model. For both investigated sites, age-depth curves modelling was performed in the
15
16 OxCal v. 4.4.4 software (Bronk Ramsey 2009, 2021) by applying the P_sequence function,
17
18 interpolation = 2 (0.5 cm), parameters $k_0 = 1$ and $\log_{10}(k/k_0) = U(-1,1)$ and using the
19
20 IntCal20 calibration curve. In the construction of the age-depth models for both sites the
21
22 *Boundary command* was applied at depths of distinctive changes recorded in the lithological
23
24 and/or biotic proxies. A mean (μ) value of the modelled age (rounded to tens, expressed in cal
25
26 BP) and sedimentation rate (expressed in mm year^{-1}), were acquired (additional information
27
28 on the radiocarbon dating in Supplemental Material).
29
30
31
32
33
34

35 ***Loss on ignition and peat type***

36
37 For loss on ignition analysis (LOI) sampling interval was equal to 2.5 cm (Figure 2 A). The
38
39 ignition process was conducted in a muffle furnace at 550°C following the standard procedure
40
41 of Heiri et al. (2001). Weight loss of the burned organic sediment expressed in % was plotted
42
43 as the loss on ignition curve. Peat type characteristics was assigned according to the previous
44
45 study of the Klaklowo and Kotoń landslide fens (Margielewski, 2001a, 2001b; Margielewski
46
47 et al., 2003) in which it was obtained through plant tissue analysis based on peat classification
48
49 of Tołpa et al. (1967).
50
51
52
53
54
55

56 ***Plant macrofossil analysis***

1
2
3 For plant macrofossil analysis, the sediment core of the Kotoń fen was sampled with the
4 higher resolution (2.5 cm thick slices) in the depth section of 500–300 cm (and additionally in
5 270–260 and 80–70 depth intervals) and with the lower resolution (2.5 cm thick slices
6 collected every 5 cm) in the depth section of 300–0 cm (Figure 2 A). In case of the Klakłowo
7 fen, sediment core was sampled with the higher resolution (2.5 cm thick slices) in the depth
8 interval 367–250 cm (some denser sampling was also applied between 250 and 220 cm),
9 whereas 250–0 cm depth interval was sampled with the lower resolution (2.5 cm thick slices
10 collected every 5 cm) (Figure 2 A).
11
12
13
14
15
16
17
18
19
20

21 Material of the samples was disaggregated in water and devoid of humic acid by
22 addition of KOH, and it was subsequently gently washed with running water through 200 µm
23 diameter mesh sieve. Taxa determination based on macrofossils of plants (fruits, seeds,
24 needles, oospores) and – to a much lesser degree - of animals (e.g. gemmules, statoblasts,
25 ephippia) was performed under ZEISS a Stemi 508 stereomicroscope at 10–16x
26 magnifications with a use of a collection of modern diaspores and specimens of fossil flora
27 from the National Biodiversity Collection of Recent and Fossil Organisms gathered at W.
28 Szafer Institute of Botany PAS in Kraków (herbarium KRAM) along with various keys and
29 publications (see references and additional information in Supplemental Material). Botanical
30 nomenclature for vascular plants was adopted according to Mirek et al. (2020), whereas
31 ecological indicators of plants were taken mostly from Zarzycki (2002) and other references
32 cited in the text. Using Tilia software (Grimm 1991), macrofossil diagrams for both sites were
33 prepared.
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53

54 ***Pollen and non-pollen palynomorphs (NPPs) analysis***

55 In this paper we use the previous pollen dataset from the Kotoń fen (Margielewski, 2001b;
56 Margielewski et al., 2003) (distance from the current drilling spot equals ca. 0.5 m) and the
57
58
59
60

1
2
3 newly acquired pollen data from the Klaklowo fen. For the Klaklowo sediment sequence
4
5 (367–0 cm), each sample (approximately 1 cm³ of sediment volume) was taken at 5 cm
6
7 interval, whereas in the archival pollen dataset from Kotoń (450–0 cm), sampling interval
8
9 equalled ca. 10 cm for the depth section of 100–0 cm and ca. 5 cm for the depth section of
10
11 450–100 cm (the late glacial deposits) (Figure 2 A). The additional information on the pollen
12
13 analysis methods is given in the Supplemental Material. Quantitative analysis of pollen and
14
15 NPPs (using *Lycopodium* tablets) consisted of counting (under a light microscope) pollen
16
17 grains of trees and shrubs up to at least 600 per sample in case of the Klaklowo site, and up to
18
19 at least 500 per sample in case of the Kotoń site (except for the Holocene deposits in Kotoń,
20
21 in which grains were counted to at least 1000).
22
23
24

25
26 Pollen datasets obtained in the current study of the Klaklowo fen (367–0 cm), and
27
28 earlier pollen datasets of the Kotoń fen (450–0 cm) were converted to relative abundances in a
29
30 similar manner to enable comparisons. Percentage share for each given taxon was determined
31
32 from the sum of arboreal (AP – trees, shrubs and dwarf shrubs) and non-arboreal (NAP –
33
34 terrestrial herbs) plant pollen given as $\Sigma AP + \Sigma NAP = \Sigma P$. Depending on the investigated site
35
36 (KK - Klaklowo, KT - Kotoń), the following groups were excluded from this sum: taxa of
37
38 spore producing plants (KK, KT), aquatic plants (KT), indeterminable pollen (KT), corroded
39
40 pollen (KK), and non-pollen palynomorphs (KK, KT- only algae *Pediastrum*). Frequency for
41
42 taxa of these groups were calculated from the $\Sigma P +$ sum of grains from a corresponding group
43
44 = 100%. Cyperaceae was included in the herbs group, following the original pollen diagram
45
46 from Kotoń (Margielewski et al., 2003). All calculations and data plotting were done using
47
48 Tilia software (Grimm, 1991). In case of the Kotoń pollen diagram, only essential plant taxa
49
50 were presented.
51
52
53
54
55
56
57

58 ***Statistical methods and zonation***

59
60

1
2
3 Constrained incremental sum of squares cluster analysis (CONISS, Grimm 1987) was carried
4
5 out on the macrofossil and pollen data to obtain Local Macrofossil Assemblage Zones
6
7 (LMAZ) and Local Pollen Assemblage Zones (LPAZ) of the Klaklowo and Kotoń fen
8
9 deposits. For this purpose, absolute counts of macrofossil data were standardized to the same
10
11 volume for the given site (Klaklowo to 20 cm³, Kotoń to 16 cm³), whereas in case of pollen
12
13 datasets, the percentage data were used. The number of statistically significant zones for
14
15 macrofossil and pollen zonations from the Klaklowo and Kotoń fens was determined based on
16
17 the broken stick model (Bennett, 1996). All calculations were performed using package Rioja
18
19 (Juggins, 2022) in R version 4.2.2 (R Core Team, 2022). The final depth ranges of the LMAZ,
20
21 LPAZ and palaeoecological stages of development were determined based on the cluster
22
23 analysis results and visual inspection of the macrofossil and pollen diagram.
24
25
26
27
28
29

30 ***Comparative diagrams and representative taxa***

31
32 To determine and compare the timing of changes in vegetation composition and lithological
33
34 data, a summary comparative diagrams in the time domain were constructed for the Klaklowo
35
36 and Kotoń fen deposits using Tilia software (Grimm, 1991). The diagrams contain the
37
38 comparison of stages of the local palaeoecological development (along with LMAZ and
39
40 LPAZ and lithological zones) and selected representative plant taxa and lithological data. As
41
42 plant macrofossil analysis corroborates the pollen analysis by confirming the local presence of
43
44 species, from among the identified plant taxa the ones which: i) show high abundance and
45
46 continuous presence throughout the sediment sequences, ii) are (if possible) present in both
47
48 pollen and macrofossil datasets and iii) are habitat-indicative, were selected for the
49
50 comparative analysis. They included: (boreal) forest-forming taxa (Coniferae, *Pinus*, *Larix*
51
52 *decidua*, *Betula* sect. *Albae*), taxa of open-space habitats (NAP sums, *Artemisia*), taxa of mire
53
54 habitats (Cyperaceae, *Carex*, Bryopsida). The last group, the proxies of allochthonous
55
56
57
58
59
60

1
2
3 material, included: indeterminable pollen (Kotoń) and corroded pollen (Klaklowo), loss on
4
5 ignition data and sedimentation rates.
6
7
8
9

10 **Results**

11 [insert Table 1]

12 [insert Figure 2]

13 *Absolute chronology and sedimentation rate*

14
15
16
17
18
19
20 The uncalibrated and calibrated AMS radiocarbon dates acquired for the Kotoń and Klaklowo
21
22 landslide fen deposits are presented in Table 1. Taking into account the time period which is
23
24 the focus of the current paper (ca. 13,900–10,000 cal BP), the age-depth models in the
25
26 corresponding depth sections (Kotoń: ca. 370–106.5 cm and Klaklowo: ca. 311.5–68.5 cm)
27
28 show varying values of sedimentation rate (Figure 2 B). For the Klaklowo fen deposits, mean
29
30 sedimentation rate amounts to 1.55 mm year⁻¹ for the 311.5–261.5 cm depth section and 2.47
31
32 mm year⁻¹ for the 261.5–240 cm depth section. Above these depths, the mean sedimentation
33
34 rate decreases: to 0.78 mm year⁻¹ for the 240–201.5 cm depth interval, to 0.50 mm year⁻¹ for
35
36 the 201.5–161.5 depth interval and to 0.24 mm year⁻¹ for the 161.5–141 cm depth interval.
37
38 For the 141–130 cm depth section, the mean sedimentation rate rises to 1.16 mm year⁻¹, and
39
40 for the 130–79.5 cm depth sections it reaches its highest value: 4.20 mm year⁻¹. Higher in the
41
42 Klaklowo profile, between 79.5 and 68.5 cm depths, it falls again to a low value, 0.10 mm
43
44 year⁻¹. For the Kotoń fen deposits, mean sedimentation rate yields the highest value, 2.95 mm
45
46 year⁻¹, for 370–326.5 cm depth section. Above this interval, the values of mean sedimentation
47
48 rate are lower: 1.01 mm year⁻¹ for the 326.5–264.5 cm depth section, 0.64 mm year⁻¹ for the
49
50 264.5–181 cm depth section and 0.98 mm year⁻¹ for the 181–120.5 cm depth section. The
51
52 lowest mean sedimentation rate occurs between 120.5–106.5 cm and equals 0.12 mm year⁻¹.
53
54
55
56
57
58
59
60

1
2
3 [insert Figure 3]
4

5 ***Loss on ignition and peat type***
6

7 The obtained loss on ignition curves for the Kotoń and Klaklowo fen deposits along with their
8 lithological characteristics (sediment type, peat type) and divisions into lithological zones are
9 given in Figure 3 C. The detailed description of these zones is given in SM Table S3 and
10 Table S4 (Klaklowo and Kotoń, respectively). Generally, in case of both sites the bottommost
11 zones (KK-L1, KT-L1 and KT-L2) are represented by minerogenic deposits composed mainly
12 of clayey silt which yield low LOI values, up to 10%. Zones from KK-L2 to KK-L7 and from
13 KT-L3 to KT-L12 correspond to accumulation of organic deposits, mostly moss fen peat,
14 yielding high LOI values, up to 80%, contaminated with minerogenic material (which at some
15 depths form distinct horizons). Zones KK-L8 and from KT-L12 to KT-L14 are largely
16 characterized by accumulation of minerogenic cover (clay), expressed as a decrease in the
17 LOI values. Zones KK-L9 and KK-L15 reflect the accumulation of sedge peat of the present
18 day Kotoń and Klaklowo fens.
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41

42 [insert Figure 4]
43

44 [insert Figure 5]
45

46 ***Macrofossil data***
47

48 The results of macrofossils analysis of the Klaklowo and Kotoń fen deposits along with
49 division into LMAZ and palaeoecological stages of development are given in Figure 4 and
50 Figure 5, respectively. Additionally, CONISS dendrograms are given in the SM Figure S3 and
51 Figure S4, respectively. In total, 18 local macrofossils assemblage zones (KK-M1 to KK-
52 M18) and eight local palaeoecological stages of development (KK-1 to KK-8) were
53 distinguished for the Klaklowo fen deposits (Figure 4 and Figure 6), whereas for the Kotoń
54 fen deposits, 16 LMAZ units (KT-M1 to KT-M16) and nine stages (KT-1 to KT-M9) were
55
56
57
58
59
60

1
2
3 established (Figure 5 and Figure 6). Descriptions of LMAZ are included in the SM Table S5
4
5 (Klaklowo) and Table S6 (Kotoń).
6
7
8
9

10 ***Pollen and NPPs data***

11
12 The results of pollen analysis of the Klaklowo and Kotoń fen sediment sequences along
13
14 with division into LPAZ are given in SM Figure S5 and Figure S6, respectively. Additionally,
15
16 CONISS dendrograms are given in the SM Figure S7 and Figure S8, respectively. In total, 11
17
18 local pollen assemblage zones (KK-P1 to KK-P11) were recognized for the Klaklowo fen
19
20 deposits (SM Figure S5), whereas for the Kotoń fen deposits, 12 LPAZ units (KT-P1 to KT-
21
22 P12) were determined (SM Figure S6). Descriptions of LPAZ are contained in the SM Table
23
24 S7 (Klaklowo) and SM Table S8 (Kotoń).
25
26
27
28
29
30

31 **Interpretation and discussion**

32
33 [insert Figure 6]

34
35 [insert Figure 7]

36 37 ***Correlation of palaeoecological records between Kotoń and Klaklowo fens with a reference*** 38 39 ***to the Greenland ice cores absolute chronology***

40
41
42 The detail interpretation of the palaeoecological stages of the Klaklowo and Kotoń landslide
43
44 fens development within the investigated time period (from ca. 13,900 to ca. 10,000 cal BP),
45
46 based on the lithological, macrofossils and pollen proxies, is given separately for each site in
47
48 the Supplemental Materials. Herein, the obtained results were compared within the
49
50 timeframes of the extraregional absolute chronology of the Greenland ice cores (INTIMATE
51
52 event stratigraphy) (Rasmussen et al., 2014) (ages b2k of the INTIMATE record recalculated
53
54 to ages before 1950 and expressed as years BP) and observations were made whether and how
55
56 the climatic changes (GI-1a–c/Allerød, GS-1/Younger Dryas, Preboreal phase and the
57
58
59
60

1
2
3 supposed Preboreal/Boreal phase) were registered in the sediments of the Kotoń and
4
5 Klaklowo fens. The graphical comparison of the palaeoecological stages and the Greenland
6
7 ice cores absolute chronology in time domain is presented in Figure 6 and the selected
8
9 representative plant taxa and lithological proxies in time domain are shown in Figure 7.
10
11
12
13

14
15 *Climatic warming GI-1a–c/Allerød (ca. 13,904–12,846 years BP)*

16
17 Record of the first climatic episode of the Allerød warming, GI-1c3 spanning ca.
18
19 13,904–13,610 years BP, differs between the two sites in regard to the development of the
20
21 local habitats: in the Klaklowo site the occurrence of an overgrowing landslide lake with
22
23 dominant sedimentation of minerogenic material were detected (stage KK-3a and 3b, Figure
24
25 6) (Pilch et al., 2025b), while at Kotoń (as a result of overgrowing of a previously existing
26
27 waterbody) at the same time the development of a fen with the accumulation of moss fen peat
28
29 had already begun (stages KT-3, KT-4a and KT-4b, Figure 6) (Pilch et al., 2025a). Only at the
30
31 time of ca. 13,610 cal BP (with the onset of the GI-1c2 phase) a fen (with the accumulation of
32
33 moss fen peat) developed at the Klaklowo site as well (stage KK-4).
34
35
36

37
38 The abundant and continuous presence of tree birch reflecting the local establishment of
39
40 *Betula* woodlands was recorded first at the Kotoń site, ca. $13,810 \pm 70$ cal BP, and
41
42 subsequently in the Klaklowo site, ca. $13,710 \pm 53$ cal BP, so during the first part of the GI-
43
44 1c3 episode of the Allerød warming (Figure 7). The abundant and continuous occurrence of
45
46 *Pinus sylvestris* macrofossils manifesting the local establishment of pine woodlands took
47
48 place slightly later and synchronously on both sites, ca. $13,650 \pm 103$ cal BP in the Kotoń site
49
50 and ca. $13,630 \pm 43$ cal BP in the Klaklowo site (Figure 7). Appearance of pine in other
51
52 localities is dated as slightly older, e.g. the Gerzensee Lake/Swiss Plateau at ca. 13,830 yr BP
53
54 (Ammann et al., 2013) or mire deposits from SE Poland at $13,770 \pm 120$ cal BP (Kończek et
55
56 al., 2015). Generally, toward the end of Allerød/beginning of Younger Dryas, the trend of
57
58
59
60

1
2
3 increasing predominance of *Pinus* pollen and (with some disruptions) also *Pinus sylvestris*
4
5 macroremains was established in the Kotoń and Klaklowo sites, what stay in agreement with
6
7 pollen and/or macrofossil data from other localities within and around the Carpathians which
8
9 document various forms of pine-dominated forests throughout Allerød (Hájková et al., 2015;
10
11 Harmata, 1987; Kołaczek et al., 2015; Latałowa and Nalepka, 1987; Magyari et al., 2012;
12
13 Margielewski et al., 2022a; Obidowicz, 1996; Pató et al., 2020; Roleček et al., 2020). The
14
15 abundant and continuous record of the *Larix decidua* at Klaklowo sites starts from around
16
17 13,540 ± 28 cal BP, indicating that this taxon could be a significant constituent of the already
18
19 developed boreal forest.
20
21
22
23
24
25

26 *Climatic cooling of the GI-1b/Gerzensee oscillation (13,261–13,049 years BP)*

27
28 A cold climatic GI-1b/Gerzensee oscillation which lasted between 13,261 and 13,049 years
29
30 BP possibly influenced in a distinctive way only the record of the Klaklowo fen. At a depth
31
32 between 217.5 and 207.5 cm, there is a noticeable minerogenic insert which age of beginning
33
34 can be determined at ca. 13,170 ± 81 cal BP (Figure 7). Correspondingly, at a depth of 212.5
35
36 cm in the pollen and macrofossil data a decreased share of pine accompanied by an increased
37
38 amount of birch and corroded pollen can be noticed, dated to 13,140 ± 79 cal BP. These dates
39
40 fit well within the timeframe of the Gerzensee oscillation. In contrast to the Klaklowo record,
41
42 in SE Poland this climatic cooling was reflected in a reduction of *Betula* pollen accumulation
43
44 rate and macrofossils abundance and a slight recession of woodland during the period
45
46 between ca. 13,120 ± 60 and 12,870 ± 60 cal BP (Kołaczek et al., 2015). Gerzensee
47
48 oscillation was visible in the pollen and macrofossil sequences of Lake Brazi and Lake Gales
49
50 in the Retezat Mts. of of Romanian Carpathians (Magyari et al., 2012), whereas in Lake
51
52 Gerzensee deposits (Swiss Plateau) it was weakly registered (Ammann et al., 2000, 2013;
53
54 Lotter et al., 1992).
55
56
57
58
59
60

1
2
3
4
5 *Climatic cooling GS-1/Younger Dryas (ca. 12,846–11,653 years BP)*
6

7
8 During the time period of ca. 12,846–11,653 years BP (the GS-1/Younger Dryas climatic
9
10 cooling), record of the local habitats development in the Kotoń and Klaklowo sites shows
11
12 certain (however not precisely simultaneous) similarities: in the earlier part it is a continuation
13
14 of peat accumulation in the less wet environment with a large admixture of minerogenic
15
16 material (upper parts of the stages KT-5a and KK-5a, respectively, Figure 6 and 7), while in
17
18 the later part it is the waterlogging of the environment and the accumulation of moss peat
19
20 without clastic admixtures (lower parts of the stages KT-5b/KT-M10 and KK-5b/KK-M13,
21
22 respectively, Figure 6 and 7).
23
24

25
26 During the GS-1/Younger Dryas, *Pinus sylvestris*-type pollen shows the maximum
27
28 percentage in the entire pollen sequences, both in Kotoń (KT-P6-*Pinus*) and Klaklowo (KK-
29
30 P7-*Pinus*-NAP) sites (Figure 6 and 7). The local presence of pine boreal forest was also
31
32 reflected in the abundant macrofossils of this taxon in the Klaklowo (upper part of the stage
33
34 KK-5a) and less numerous in Kotoń fen (stage KT-5a/KT-M8 and M9) (Figure 6 and 7).
35
36 Birch tree was probably the second major woodland-forming component at that time, what is
37
38 reflected in numerous macrofossils found in both sites. However, in the upper part of the GS-
39
40 1/Younger Dryas in the Klaklowo fen record (stage KK-5b/KK-M13, Figure 6 and 7) almost a
41
42 total disappearance of *Betula* sect. *Albae* and a strong reduction in the number of *Pinus*
43
44 *sylvestris* macrofossils can be observed (however not visible in pollen data), what in
45
46 combination with a slight increase in *Artemisia* pollen percentage could be attributed to the
47
48 woodland opening and some inclusion of more open-space plant communities. In a similar
49
50 manner, the expansion of grassland communities was correlated in time with the scarcity of
51
52 macrofossils of *Betula* sect. *Albae* in the Romanian Carpathians during 12,950–11,500 cal BP
53
54 (Feurdean and Bennike, 2004). Furthermore, in the SE Poland, the co-occurrence of well-
55
56
57
58
59
60

1
2
3 developed (more resilient to climate changes) dense pine forest and steppe communities was
4 explained by steppe expansion onto tundra patches and/or filling the space after the decline of
5 tree birch (Kořaczek et al., 2015). Nevertheless, the steppe-tundra signal in Klaklowo record
6
7
8
9
10 during GS-1/Younger dryas remains very weak. In the Kotoń fen, the increase in NAP and
11
12
13 *Artemisia* pollen relative abundances can be distinctively observed only around ca. 11,900 cal
14
15 BP (LPAZ KT-P7, Figure 6 and 7).

16
17 Apart from the Kotoń and Klaklowo localities, the persistence of pine forest (also with
18 tree birch and larch) during the climatic reversal of ca. 12,846–11,653 years BP, was traced
19
20
21 (with various intensity) also in the sediment sequences of the other sites in the Carpathians
22
23 and the adjacent regions: at the Grel raised bog in the Orawa-Nowy Targ Basin (Margielewski
24 et al., 2022a), at Preluca Tiganului in Gutaiului Mountains, NW Romania (Feurdean and
25 Bennike, 2004), at Dářko peat bog in the central Czech Republic (Roleček et al., 2020) and on
26
27
28 the N slopes of the Matra Mountains in N Hungary (Pató et al., 2020).

32 33 34 35 *Climatic warming of the Preboreal phase (ca. 11,653–11,250 years BP)*

36
37 The beginning of the Holocene (Preboreal phase) at ca. 11,653 years BP is manifested by a
38 gradual intensification of the supply of minerogenic material to the Kotoń and Klaklowo fens
39
40
41 (zones KT-L10 and KK-L5, respectively, Figure 6). In the LOI curves of both sites this trend
42
43
44 is synchronously visible since ca. $11,720 \pm 123$ cal BP for Kotoń and ca. $11,720 \pm 178$ cal BP
45
46
47 for Klaklowo fen (Figure 7), so slightly earlier than the GS-1 ending. This could be partly
48
49 attributed to the less cold second part of the Younger Dryas, determined in SE Poland
50
51
52 (Kořaczek et al., 2015).

53
54 With the beginning of the Preboreal phase also the important changes in the plant taxa
55
56
57 composition can be observed in both sites. In the upper part of the Klaklowo and Kotoń fens'
58
59 stage 5b (LMAZ KK-M14 and KT-M11, respectively, Figure 6), there is an ultimate almost
60

1
2
3 simultaneous decline of Bryopsida at a time of $11,510 \pm 161$ cal BP and $11,560 \pm 177$ cal BP,
4
5 respectively, which group do not reappear anymore in both profiles (Figure 7). Moreover, in
6
7 the Kotoń macrofossil record a total disappearance was detected in case of so-far continuously
8
9 present and abundant taxa: *Pinus sylvestris* needles ($11,670 \pm 142$ cal BP), Coniferae bud
10
11 scales ($11,614 \pm 160$) and (slightly later) *Larix decidua* ($11,460 \pm 208$ cal BP).
12
13
14
15
16

17 *The supposed Preboreal oscillation (ca. 11,250–11,000 cal BP)*

18
19 In the sediment sequences of both sites the short-lasting stage 6 was delineated (KT-6, KK-6)
20
21 based on the huge minerogenic input (i.e. decrease of LOI values) (Figure 6 and 7). In both
22
23 cases, this event has relatively short duration and a similar time of onset: in Kotoń fen it lasted
24
25 from ca. $11,260 \pm 263$ to ca. $10,990 \pm 432$ cal BP, ca. 270 years, whereas in Klakłowo fen
26
27 from ca. $11,240 \pm 92$ to ca. $11,120 \pm 99$ cal BP, ca. 120 years. There is, however, an
28
29 enormous difference in the accumulated sediment thickness of this interval: in case of Kotoń
30
31 it equals ca. 7.5 cm, whereas for Klakłowo ca. 47.5 cm, what is the result of the strikingly
32
33 higher sedimentation rate for the latter site: ca. $4.20 \text{ mm year}^{-1}$ comparing to ca. 0.98 mm
34
35 year^{-1} in case of Kotoń. Taking into consideration the starting time of the stage KT-6 and KK-
36
37 6, ca. 11,260 or 11,240 cal BP, respectively, it could correspond to the cold Preboreal
38
39 oscillation (Ammann et al., 2000), however this oscillation was attributed to the various cold
40
41 events (differing in time extent) recognised in the early Holocene deposits across Europe
42
43 (Filoc et al., 2018). Similarly to the Kotoń and Klakłowo records, a phenomenon of enhanced
44
45 minerogenic delivery at ca. 11,250 cal BP was detected in the Romanian Carpathians,
46
47 Gutaiului Mountains, NW Romania (Feurdean and Bennike, 2004). At Grel raised bog, the
48
49 the Orawa-Nowy Targ Basin, in peat sedimentary sequence of the Preboreal Phase ($11,173$ –
50
51 $10,775$ cal BP) the illuvial horizon was formed as a result of flooding episode and was
52
53 attributed to the Preboreal cold oscillation (Margielewski et al., 2022a).
54
55
56
57
58
59
60

1
2
3 During the supposed Preboreal oscillation, there are also prominent changes in biotic
4 records. In case of Kotoń site, stage KT-6 is the last time of occurrence of *Betula pubescens*
5 and so-far occurring *Carex* species, yielding the dates of decline of ca. $11,205 \pm 277$ and ca.
6 $10,987 \pm 432$, respectively (Figure 7). In the Gutaiului Mountains, NW Romania the reduction
7 in *Carex* ssp. remains was observed between 11,000 and 10,300 cal BP and explained by the
8 rise of water level (Feurdean and Bennike, 2004). Stage KT-6 corresponds also to LPAZ KT-
9 P8 (Figure 6), signaling the more open-space conditions with domination of herbs and
10 shrinkage of woodlands. In case of the Klaklowo fen, at the end of the stage KK-6, there is a
11 recession of all *Carex* species ($11,140 \pm 88$ cal BP), an almost total disappearance of *Pinus*
12 *sylvestris* and a total decline of *Larix decidua* and *Betula* sect. *Albae* (all three taxa
13 disappearances are dated to ca. $11,120 \pm 99$ cal BP) (Figure 7). In contrast to Kotoń, in the
14 pollen record from Klaklowo during the supposed Preboreal oscillation pine forest seems to
15 be still a dominant vegetation type (LPAZ KK-P8, Figure 6 and 7).

35 *The supposed Preboreal/Boreal phase (ca. 11,000–10,000 cal BP)*

36
37 The supposed Preboreal/Boreal period (not possible to separate) in the Kotoń and Klaklowo
38 sediment sequences seems to correspond to the stages KT-7 and KK-7, which began ca.
39 $10,990 \pm 432$ and ca. $11,120 \pm 99$ cal BP, respectively, and share many common features
40 (Figure 6). At both sites, the lowest sedimentation rate of the whole profiles was determined,
41 $0.12 \text{ mm year}^{-1}$ for Kotoń and ca. $0.10 \text{ mm year}^{-1}$ for the Klaklowo deposits (Figure 7). In
42 both fens some minerogenic-organic deposits were accumulated at that time: in the Kotoń fen
43 sedge-moss fen peat with minerogenic admixture (maximum LOI value: ca. 30%) and the
44 Klaklowo fen woody birch peat with contamination of minerogenic material (maximum LOI
45 value: ca. 35%) (Figure 7). In relation to the plant remains, in both fens within the supposed
46 Preboreal/Boreal phase abundant fruits of *Scirpus sylvaticus* and sclerotia of *Cenococcum*
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3 *geophilum* were found (Figure 4 and 5), the latter confirming the process of strong erosion
4 and re-deposition of allochthonous material to the fen basin. Also the corresponding LPAZ
5 units from both sites show similar trends (SM Figure S5 and S6): next to the still dominating
6
7
8
9
10 *Pinus sylvestris*-type, pollen relative abundances of several other arboreal taxa start to rise and
11
12 develop into continuous curves: *Picea abies*, *Ulmus*, *Alnus* undiff., *Corylus avellana* and *Tilia*
13
14 undiff, marking the development of temperate mixed forests in the warming climate of the
15
16 Holocene (Feurdean and Bennike, 2004; Margielewski et al., 2022a; Roleček et al., 2020). In
17
18 the Klaklowo fen, this climatic change is also reflected in the enhanced input of corroded
19
20 pollen (Figure 7).
21
22

23
24
25
26 ***Do the records of the late glacial-early Holocene climatic oscillations differ between Kotoń***
27
28 ***and Klaklowo landslide fens in relation to their different topographic position?***

29
30 ***Similarities and differences between the Kotoń and Klaklowo vegetation records***

31
32 Records of vegetation changes inferred from the Kotoń and Klaklowo deposits between ca.
33
34 13,900 and ca. 10,000 cal BP show more similarities than differences (SM Table S9). The
35
36 similarities not coinciding but shifted in time concerns changes of the local habitats'
37
38 succession, e.g. the phases of the long-lasting fen stage during GI-1a–c/Allerød, GS-
39
40 1/Younger Dryas and at the beginning of the Preboreal phase are equivalent but not occurring
41
42 at the same time (Figure 6): the less wet stage of 5a lasts longer at the Kotoń site, whereas in
43
44 Klaklowo it finishes sooner and change into the stage 5b/KK-M13 of fen waterlogging. The
45
46 other mentioned diachronous similarities concern the local establishment of *Betula* woodlands
47
48 during GI-1c3/Allerød in both fens and regional temperate mixed forests expansion initiated
49
50 during the supposed Preboreal/Boreal phase (Figure 7, SM Figure S5 and S6). The occurrence
51
52 of these similar but not simultaneous phenomena could be influenced by the differences in the
53
54 local fen conditions, e.g. varying characteristics of the sub-scarps depressions occupied by
55
56
57
58
59
60

1
2
3 fens (e.g. shape, extent, depth and relief, Figure 1) and diverse hydrogeological conditions
4
5 (e.g. dynamics of groundwater table, occurrence and number of watercourses, Figure 1)
6
7 (Hubay et al., 2018; Micheczyński et al., 2013). On the other hand, in case of the differing
8
9 timing of the deciduous trees expansion during the supposed Preboreal/Boreal phase, the high
10
11 uncertainty values of the radiocarbon modelled age should be also taken into consideration
12
13
14 (Magyari et al., 2018).
15
16

17 The synchronous similarities observed between the vegetation records of the Kotoń
18
19 and Klaklowo fens include the timing of the local presence/establishment of pine woodlands
20
21 and its expansion toward the end of Allerød/beginning of Younger Dryas and maximum
22
23 development of the pine forest during the GS-1/Younger Dryas climatic cooling (Figure 6 and
24
25 7). The global-scale climatic warming of the GI-1/Bølling-Allerød caused the longer duration
26
27 of the growing season and an increase in summer temperatures, enhancing pollen and seeds
28
29 productivity of pine and birch, and the expansion of forests composed of these taxa (Feurdean
30
31 et al., 2007). Furthermore, another global climatic factor possibly triggered the ultimate
32
33 (almost concordant) decline of Bryopsida at the beginning of the Holocene (Preboreal phase)
34
35 when increase in temperature and humidity, permafrost degradation and subsequent changes
36
37 in the water circulation (perhaps lowering of the groundwater level in the fens) could cause
38
39 the ending of the long-lasting (dominated by brown mosses) fen stage at both sites (Latałowa
40
41 and Nalepka, 1987). Therefore, the synchronous and similar changes in vegetation cover
42
43 recognized in the Kotoń and Klaklowo fen deposits are visibly govern by the strongest and
44
45 long-term global climatic shifts (Allerød, Younger Dryas, Holocene) and show no prominent
46
47 dependency on the altitude and exposure of the sites (Ammann et al., 2000). The evident
48
49 simultaneous response to the main climatic phases at all elevations is confirmed also by other
50
51 studies, additionally showing that the strongest climatic signal and also some weaker
52
53
54
55
56
57
58
59
60

1
2
3 secondary climatic fluctuations were registered at mid altitudes (e.g. 800–1100 m a.s.l),
4
5 presumably due to the proximity of the tree line ecotone (David, 1993; Feurdean et al., 2007).
6

7
8 The differences between vegetation records of the Kotoń and Klaklowo fens can be
9
10 observed in the dynamics of the *Larix decidua* population. The much earlier expansion and
11
12 later recession of the European larch (along with *Pinus sylvestris* and Coniferae) in the
13
14 Klaklowo fen than in the Kotoń fen (Figure 7) could be attributed to the northern exposure of
15
16 the former site. Magyari et al. (2018) showed that European larch spread earlier on the
17
18 northern slopes of the Retezat Mts. in the Romanian Carpathians and suggested that the last
19
20 glacial maximum survival of this species was also on the northern slopes. An example of the
21
22 coniferous species refugium which allowed for the withstanding of the boreal European larch-
23
24 Swiss stone pine (*Larix decidua*-*Pinus cembra*) forest long into the Holocene (up to 7700 cal
25
26 BP) was found on the northerly exposed slopes in the Matra Mountains (Nagy-forras forest
27
28 hollow, 685 m a.s.l.) (Pató et al., 2020). Although currently during the growing season areas
29
30 within Klaklowo and Kotoń fen boundaries seem to exhibit similar conditions for plant
31
32 growth in term of solar irradiation (Supplemental Material, SM Figure S1 and Figure S2),
33
34 during the early Holocene the diversified relief of the landslide area around the fens could
35
36 strengthen the refugial potential of the Klaklowo site (Šímová et al., 2019) and allowed for the
37
38 longer occurrence of *Larix decidua*, *Pinus sylvestris* and Coniferae on the northern slopes of
39
40 the Mt. Kotoń-Mt. Pękalówka massif.
41
42
43
44
45
46
47
48
49

50 *Similarities and differences between the Kotoń and Klaklowo lithological records*

51
52 Records of the minerogenic sediment delivery to the Kotoń and Klaklowo landslide
53
54 fens between ca. 13,900 and ca. 10,000 cal BP show more differences than similarities (SM
55
56 Table S9). The approximately synchronous beginning of the enhanced supply of minerogenic
57
58 material to the fens at ca. 11,720 cal BP indicates humidity rise, permafrost degradation,
59
60

1
2
3 changes in the water circulation, slope instability and soil exposure to erosion and surface
4 runoff caused by the strong global-scale climatic warming of the Holocene (Pánek et al.,
5
6
7 2010; Rubensdotter and Rosqvist, 2003; Šímová et al., 2019). Important factor enabling the
8
9
10 slope erosion could be the reduction of the forest cover around the fens: at the Younger
11
12 Dryas/Preboreal transition at both sites an increase in NAP/*Artemisia* pollen percentages can
13
14
15 be observed (Figure 6 and 7).

16
17 In relation to differences in minerogenic material delivery, the results show that
18
19 Klaklowo fen exclusively records: a thin minerogenic intercalation at ca. $13,490 \pm 25$ cal BP
20
21 (difficult to attributed to any common climatic event) and lithological and pollen responses to
22
23 the supposed GI-1b/Gerzensee oscillation. The supposed cold Preboreal oscillation seems to
24
25 affect the deposits of both sites in the rather abrupt way, however, in case of the Klaklowo
26
27 landslide fen (ca. $11,240 \pm 92$ to ca. $11,120 \pm 99$ cal BP, ca. 120 years) the thickness of
28
29 deposits is much greater (47.5 cm comparing to 7.5 cm in Kotoń) what results from a very
30
31 high sedimentation rate ($4.20 \text{ mm year}^{-1}$). This difference could be explained by much greater
32
33 availability of slope material prone to erosion in case of Klaklowo fen since its catchment area
34
35 is ca. 3 times greater than the area of the Kotoń fen's possible palaeo catchment and ca. 12
36
37 times greater than its present-day catchment (Figure 1 G and H, see detail description in
38
39 Supplemental Material). Furthermore, Klaklowo fen drainage area has an elongated shape and
40
41 span from the crest of Mt. Pękalówka downward the slope and encompass the whole
42
43 semicircular head scarp of the Klaklowo landslide (up to ca. 550 m of denivelation, Figure 1
44
45 H), giving access to the higher energy for sediment transportation (Rubensdotter and
46
47 Rosqvist, 2003), whereas in the Kotoń fen catchment, flow of water drains only the western
48
49 part of the Kotoń landslide in case of both possible palaeo- and the present-day catchments
50
51 and has much smaller relief (Figure 1 G). Another contrast lies in the bedrock geology: while
52
53 Kotoń fen catchment drains the area entirely built of thick-bedded Magura sandstones,
54
55
56
57
58
59
60

1
2
3 bedrock of the Klaklowo fen catchment is more diverse and includes also easily removable
4
5 shales (Figure 1 F).
6

7
8 Interestingly, the greater potential for the minerogenic influx in case of the Klaklowo
9
10 fen catchment is not reflected in the shorter sediment sequence of the Klaklowo fen deposits
11
12 comparing to the Kotoń fen (Rubensdotter and Rosqvist, 2003). Furthermore, the possible
13
14 catastrophic scale of the supposed Preboreal sediments deposition in the Klaklowo fen need to
15
16 be further clarified in combination with the questionable reliability of the age-depth model at
17
18 this depth interval (Magyari et al., 2018). For example, the well visible minerogenic layers
19
20 related to the GI-1b/Gerzensee oscillation and the supposed Preboeral oscillation (a clayey silt
21
22 horizon from a depth of ca. 112.5–97.5 cm dated to $11,200 \pm 80$ cal BP) could have been
23
24 accumulated in Klaklowo fen during a single fen inundation caused by some
25
26 hydrometeorological event (continuous rains) (Margielewski, 2018).
27
28
29
30
31

32 33 **Conclusions**

34
35 Results of the multi-proxy analysis carried out for the late glacial-early Holocene (ca.
36
37 13,900–10,000 cal BP) deposits of the Kotoń and Klaklowo landslide fens in relation to their
38
39 different topographic positions revealed that:
40
41

- 42 1. The identified time shift in occurrence of the similar vegetation changes (e.g. long-
43
44 lasting fen succession, birch tree expansion) in the Kotoń and Klaklowo fen deposits
45
46 probably results from the differing local physical conditions of the fens (e.g. shape,
47
48 extent, depth and relief of the sub-scarps depressions, dynamics of groundwater table,
49
50 occurrence and number of watercourses). On the contrary, the synchronous similarities
51
52 in vegetation records (e.g. pine forest expansion at ca. 13,650 and ca. 13,630 cal BP,
53
54 Bryopsida recession at ca. 11,560 and 11,510 cal BP and ending of the long-lasting fen
55
56 stage dominated by brown mosses) are visibly govern by the strongest and long-term
57
58
59
60

1
2
3 global climatic changes (GI-1a–c /Allerød, GS-1/Younger Dryas, Holocene) and show
4
5 no striking dependency on the altitude and/or exposure of the sites.
6
7

- 8 2. The approximately simultaneous beginning of the enhanced supply of minerogenic
9
10 material to the Kotoń and Klaklowo fens at ca. 11,720 cal BP, shows that strong
11
12 climatic reversal of the Holocene can trigger the similar and synchronous pattern in
13
14 lithological record of both fens regardless their topographic position. On the contrary,
15
16 the fen catchment characteristics, including area, shape, relief, bedrock geology and
17
18 specific local landforms, could contribute to the much more pronounced lithological
19
20 record of the weaker and shorter climatic oscillations, the GI-1b/Gerzensee oscillation
21
22 and Preboreal oscillation, as it was observed in case of the Klaklowo fen deposits. The
23
24 intense sedimentation during the Preboreal oscillation need to be, however, further
25
26 clarified due to questionable reliability of the age-depth model at this depth.
27
28
29
- 30 3. Based on the gathered observations, the hypothesis that the late glacial-early Holocene
31
32 climatic changes were recorded differently between the Kotoń landslide fen
33
34 characterized by the southern exposure and near-ridge position and the Klaklowo
35
36 landslide fen characterized by the northern exposure and mid-slope position, can be
37
38 confirmed for the smaller-scale climatic oscillations, including GI-1b/Gerzensee
39
40 oscillation and the supposed Preboreal oscillation. Expansion and/or decline of the
41
42 dominating vegetation taxa (*Pinus*, *Betula* sect. *Albae*, *Carex*, Bryopsida) and
43
44 minerogenic delivery induced by the global-scale climatic reversals: GI-1a–c /Allerød,
45
46 GS-1/Younger Dryas and Holocene, occur approximately at the same time in both
47
48 Klaklowo and Kotoń landslide fens. The exception is later recession of *Larix decidua*,
49
50 *Pinus sylvestris* and Coniferae in the Klaklowo fen than in the Kotoń fen what can be
51
52 attributed to the northern exposure and diversified landslide relief of the Klaklowo
53
54
55
56
57
58
59
60

1
2
3 site. In the warming climate of the Holocene, such a setting could play a refugial role
4
5 for some boreal forest Coniferae species.
6
7
8
9

10 **Acknowledgements**

11
12 [details omitted for double-anonymized peer review]
13
14
15

16 **Author contributions**

17
18
19 [details omitted for double-anonymized peer review]
20
21
22

23 **Statements and Declarations**

24 *Ethical considerations*

25
26
27
28 [details omitted for double-anonymized peer review]
29
30
31

32 *Consent to participate*

33
34
35 [details omitted for double-anonymized peer review]
36
37
38

39 *Consent for publication*

40
41
42 [details omitted for double-anonymized peer review]
43
44
45

46 *Declaration of conflicting interest*

47
48
49 [details omitted for double-anonymized peer review]
50
51
52

53 **Funding statement**

54
55
56 [details omitted for double-anonymized peer review]
57
58
59
60

Data availability

[details omitted for double-anonymized peer review]

References

- Ammann B, Birks H, Brooks SJ, et al. (2000) Biotic responses to rapid climatic changes - an attempt to a synthesis. *Palaeogeography, Palaeoclimatology, Palaeoecology* 159: 313–347.
- Ammann B, van Leeuwen JFN, van der Knaap WO, et al. (2013) Vegetation responses to rapid warming and to minor climatic fluctuations during the Late-Glacial Interstadial (GI-1) at Gerzensee (Switzerland). *Palaeogeography, Palaeoclimatology, Palaeoecology* 391: 40–59.
- Ammann B, van der Knaap WO, Lang G, et al. (2014) The potential of stomata analysis in conifers to estimate presence of conifer trees: Examples from the Alps. *Vegetation History and Archaeobotany* 23(3): 249–264.
- Bank Danych o Lasach (2025). Available at: <https://www.bdl.lasy.gov.pl/portal/mapy> (accessed 03 May 2025).
- Bennett KD (1996) Determination of the number of zones in a biostratigraphical sequence. *New Phytologist* 132: 155–170.
- Björck S, Walker MJC, Cwynar LC, et al. (1998) An event stratigraphy for the Last Termination in the North Atlantic region based on the Greenland ice-core record: a proposal by the INTIMATE group. *Journal of Quaternary Science* 13(4): 283–292.
- Bronk Ramsey C (2009) Bayesian analysis of radiocarbon dates. *Radiocarbon* 51(1): 337–360.

1
2
3 Bronk Ramsey C (2021) Oxcal version 4.4.4. Available at: <https://c14.arch.ox.ac.uk> (accessed
4
5 13 November 2022).

6
7
8 Climate Data (2024) Stróža i Zawadka. Available at: <https://pl.climate->
9
10 [data.org/europa/polska/lesser-poland-voivodeship/stroza-450713/](https://pl.climate-data.org/europa/polska/lesser-poland-voivodeship/stroza-450713/) and <https://pl.climate->
11 [data.org/europa/polska/lesser-poland-voivodeship/zawadka-450812/](https://pl.climate-data.org/europa/polska/lesser-poland-voivodeship/zawadka-450812/) (accessed 08
12
13 August 2024).

14
15
16
17
18 David F (1993) Altitudinal variation in the response of the vegetation to Late-glacial climatic
19
20 events in the northern French Alps. *New Phytologist* 125(1): 203–220.

21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
Feurdean A and Bennike O (2004) Late Quaternary palaeoecological and
palaeoclimatological reconstruction in the Gutaiului Mountains, northwest Romania.
Journal of Quaternary Science 19(8): 809–827.

Feurdean A, Wohlfarth B, Björkman L, et al. (2007) The influence of refugial population on
Lateglacial and early Holocene vegetational changes in Romania. *Review of
Palaeobotany and Palynology* 145(3–4): 305–320.

Feurdean A, Gałka M, Tanțău I, et al. (2016) Tree and timberline shifts in the northern
Romanian Carpathians during the Holocene and the responses to environmental changes.
Quaternary Science Reviews 134: 100–113.

Fiłoc M, Kupryjanowicz M, Rządziejewicz M, et al. (2018) Response of terrestrial and lake
environments in NE Poland to Preboreal cold oscillations (PBO). *Quaternary
International* 475: 101–117.

GRASS Development Team (2015) Geographic Resources Analysis Support System
(GRASS) Software, Version 7.0. Open Source Geospatial Foundation. Available at:
<https://grass.osgeo.org> (accessed 05 April 2025).

- 1
2
3 Grimm EC (1987) CONISS: A FORTRAN 77 program for stratigraphically constrained
4
5 cluster analysis by the method of incremental sum of squares. *Computers and*
6
7 *Geosciences* 13(1): 13–35.
8
9
10 Grimm EC (1991) *TILIA and TILIA Graph*. Springfield: Illinois State Museum.
11
12
13 Hájková P, Petr L, Horsák M, et al. (2015) Interstadial inland dune slacks in south-west
14
15 Slovakia: A multi-proxy vegetation and landscape reconstruction. *Quaternary*
16
17 *International* 357: 314–328.
18
19
20
21 Harmata K (1987) Late-Glacial and Holocene history of vegetation at Roztoki and Tarnowiec
22
23 near Jasło (Jasło-Sanok Depression). *Acta Palaeobotanica* 27(1): 43–65.
24
25
26 Heiri O, Lotter A and Lemcke G (2001) Loss on ignition as a method for estimating organic
27
28 and carbonate content in sediments: reproducibility and comparability of results. *Journal*
29
30 *of Paleolimnology* 125(2): 101–110.
31
32
33
34 Hubay K, Braun M, Buczkó K, et al. (2018) Holocene environmental changes as recorded in
35
36 the geochemistry of glacial lake sediments from Retezat Mountains, South Carpathians.
37
38 *Quaternary International* 477: 19–39.
39
40
41
42 Juggins S (2022) Rioja: Analysis of quaternary science data. R package version 1.0-5.
43
44 Available at: <https://cran.r-project.org/package=rioja> (accessed 15 March 2023).
45
46
47 Kłapyta P, Zasadni J, Pociask-Karteczka J, et al. (2016) Late Glacial and Holocene
48
49 paleoenvironmental records in the Tatra Mountains, East-Central Europe, based on lake,
50
51 peat bog and colluvial sedimentary data: A summary review. *Quaternary International*
52
53 415: 126–144.
54
55
56
57 Kołaczek P, Gałka M and Karpińska-Kołaczek M (2015) Succession of arboreal taxa during
58
59 the Late Glacial in south-eastern Poland: Climatic implications. *Palaeogeography,*
60

- 1
2
3 *Palaeoclimatology, Palaeoecology* 421: 1–14.
4
5
6 Koperowa W (1961) Późnoglacialna i holocenska historia roślinności Kotliny Nowotarskiej.
7
8 *Acta Palaeobotanica* 2(3): 3–57.
9
10
11 Książkiewicz M (1972) Karpaty. In: Pożaryski W (ed.) *Budowa Geologiczna Polski, Part IV,*
12
13 *Tektonika. Vol. 3, Karpaty.* Warszawa: Wydawnictwo Geologiczne, p. 228.
14
15
16 Książkiewicz M, Rączkowski W and Wójcik A (2016) *Szczegółowa Mapa Geologiczna*
17
18 *Polski w Skali 1:50000, Arkusz Osielec.* Warszawa: Ministerstwo Środowiska.
19
20
21
22 Latałowa M and Nalepka D (1987) A study of the Late-Glacial and Holocen vegetation
23
24 history of the Wolbrom area (Silesian-Cracovian Upland). *Acta Palaeobotanica.*
25
26
27 Lotter AF, Eicher U, Siegenthaler U, et al. (1992) Late-glacial climatic oscillations as
28
29 recorded in Swiss lake sediments. *Journal of Quaternary Science* 7: 187–204.
30
31
32
33 Lowe JJ, Rasmussen SO, Björck S, et al. (2008) Synchronisation of palaeoenvironmental
34
35 events in the North Atlantic region during the Last Termination: a revised protocol
36
37 recommended by the INTIMATE group. *Quaternary Science Reviews* 27(1–2): 6–17.
38
39
40 Magyari E (2002) Holocene biogeography of *Fagus sylvatica* L. and *Carpinus betulus* L. in
41
42 the Carpathian-Alpine Region. *Folia Historico-Naturalia Musei Matraensis* (26): 15–35.
43
44
45
46 Magyari E, Jakab G, Bálint M, et al. (2012) Rapid vegetation response to Lateglacial and
47
48 early Holocene climatic fluctuation in the South Carpathian Mountains (Romania).
49
50 *Quaternary Science Reviews* 35: 116–130.
51
52
53 Magyari E, Vincze I, Orbán I, et al. (2018) Timing of major forest compositional changes and
54
55 tree expansions in the Retezat Mts during the last 16,000 years. *Quaternary International*
56
57 477: 40–58.
58
59
60

- 1
2
3 Mamakowa K (1962) Roślinność Kotliny Sandomierskiej w Późnym Glacjale i Holocenie.
4
5 *Acta Palaeobotanica* 3: 3–57.
6
7
8 Margielewski W (2001a) Late Glacial and Holocene climatic changes registered in forms and
9
10 deposits of the Klakłowo landslide (Beskid Średni Range, Outer Carpathians). *Studia*
11
12 *Geomorphologica Carpatho-Balcanica* 35: 63–79.
13
14
15 Margielewski W (2001b) Rejestr zmian klimatycznych późnego glacjału i holocenu w obrębie
16
17 torfowiska pod Kotoniem (Beskid Średni, Karpaty Zewnętrzne). *Przegląd Geologiczny*
18
19 49(12): 1161–1166.
20
21
22
23 Margielewski W (2006) Records of the Late glacial-Holocene palaeoenvironmental changes
24
25 in landslide forms and deposits of the Beskid Makowski and Beskid Wyspowy Mts. area
26
27 (Polish outer Carpathians). *Folia Quaternaria* 76. Polska Akademia Umiejętności
28
29 Komisja Paleogeografii Czwartorzędu: 1–149.
30
31
32
33 Margielewski W (2014) Torfowiska osuwiskowe polskich Karpat fliszowych jako czuły
34
35 indykator zmian paleośrodowiska późnego glacjału i holocenu. *Studia Limnologica et*
36
37 *Telmatologic* 8/1: 37–55.
38
39
40
41 Margielewski W (2018) Landslide fens as a sensitive indicator of paleoenvironmental changes
42
43 since the Late Glacial: A case study of the Polish Western Carpathians. *Radiocarbon*
44
45 60(4): 1199–1213.
46
47
48
49 Margielewski W, Obidowicz A and Pelc S (2003) Late Glacial-Holocene peat bog on Kotoń
50
51 Mt. and its significance for reconstruction of palaeoenvironment in the Western Outer
52
53 Carpathians (Beskid Makowski Range, South Poland). *Folia Quaternaria* 74: 35–56.
54
55
56 Margielewski W, Michczyński A and Obidowicz A (2010) Records of the middle - And Late
57
58 Holocene palaeoenvironmental changes in the Pcim-Sucha landslide peat bogs (Beskid
59
60

1
2
3 Makowski Mts., Polish Outer Carpathians). *Geochronometria* 35(1): 11–23.
4
5

6 Margielewski W, Michczyńska DJ, Buczek K, et al. (2022a) Towards the understanding of
7
8 the present-day human impact on peatland deposits formed since the Late Glacial: a
9
10 retrospective age-depth model of the Grel raised bog (Polish Inner Carpathians).
11
12 *Radiocarbon* 64(6): 1525–1543.
13
14

15
16 Margielewski W, Obidowicz A, Zernitskaya V, et al. (2022b) Late Glacial and Holocene
17
18 palaeoenvironmental changes recorded in landslide fans deposits in the Polish Outer
19
20 Western Carpathians (Southern Poland). *Quaternary International* 616. Pergamon: 67–
21
22 86.
23
24

25
26 Michczyński A, Kołaczek P, Margielewski W, et al. (2013) Radiocarbon age-depth modeling
27
28 prevents misinterpretation of past vegetation dynamics: Case study of Wierchomla Mire
29
30 (Polish Outer Carpathians). *Radiocarbon* 55(3): 1724–1734.
31
32

33
34 Mirek Z, Piękoś-Mirkowa H, Zając A, et al. (2020) *Vascular Plants of Poland. An Annotated*
35
36 *Checklist*. Kraków: W. Szafer Institute of Botany, Polish Academy of Sciences.
37

38
39 Obidowicz A (1996) A Late Glacial-Holocene history of the formation of vegetation belts in
40
41 the Tatra Mts. *Acta Palaeobotanica* 36(2): 159–206.
42
43

44 Pánek T, Hradecký J, Smolková V, et al. (2010) The largest prehistoric landslide in
45
46 northwestern Slovakia: Chronological constraints of the Kykula long-runout landslide
47
48 and related dammed lakes. *Geomorphology* 120(3–4): 233–247.
49
50

51 Pató ZA, Standovár T, Gałka M, et al. (2020) Exposure matters: Forest dynamics reveal an
52
53 early Holocene conifer refugium on a north facing slope in Central Europe. *Holocene*
54
55 30(12): 1833–1848.
56
57

58
59 Pilch J, Margielewski W, Stachowicz-Rybka R and Buczek K (2025a) The Bølling-Older
60

1
2
3 Dryas-Allerød transition (ca. 14,600–13,500 cal BP) in the palaeoecological record of
4 the Kotoń landslide fen (the Outer Western Carpathians, S Poland) – from the local to
5 extraregional perspective. *Radiocarbon* (in press).
6
7
8
9

10 Pilch J, Margielewski W, Stachowicz-Rybka R, Buczek K, et al. (2025b) Characeae-
11 dominated vegetation succession as a key to understanding the late glacial environmental
12 changes (ca. 14,600–13,500 cal yrs BP): a multi-proxy record of palaeo-waterbody
13 developed within the Klaklowo landslide, the Outer Western Carpathians, S Poland.
14
15
16
17
18
19
20 *Journal of Paleolimnology* 73(3): 195–215.
21

22
23 QGIS Development Team (2021) QGIS Geographic Information System. Open Source
24 Geospatial Foundation Project, Version 3.22.10. Available at: <http://qgis.org> (accessed
25 12 December 2022).
26
27
28
29

30 R Core Team (2022) R: A language and environment for statistical computing. R Foundation
31 for Statistical Computing, Vienna, Austria, <https://www.R-project.org/> (accessed 15
32 March 2023).
33
34
35
36
37

38 Ralska-Jasiewiczowa M (1980) *Late-Glacial and Holocene Vegetation of the Bieszczady Mts.*
39 *(Polish Eastern Carpathians)*. Warszawa-Kraków: Państwowe Wydawnictwo Naukowe.
40
41
42

43 Rasmussen SO, Bigler M, Blockley SP, et al. (2014) A stratigraphic framework for abrupt
44 climatic changes during the Last Glacial period based on three synchronized Greenland
45 ice-core records: Refining and extending the INTIMATE event stratigraphy. *Quaternary*
46
47
48
49
50
51 *Science Reviews* 106: 14–28.
52

53 Reimer PJ, Austin WEN, Bard E, et al. (2020) The IntCal20 Northern Hemisphere
54 radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon* 62(4): 725–757.
55
56
57

58 Roleček J, Svobodová HS, Jamrichová E, et al. (2020) Conservation targets from the
59
60

perspective of a palaeoecological reconstruction: The case study of Dářko peat bog in the Czech Republic. *Preslia* 92(2): 87–114.

Rubensdotter L and Rosqvist G (2003) The effect of geomorphological setting on Holocene lake sediment variability, northern Swedish Lapland. *Journal of Quaternary Science* 18(8): 757–767.

Šímová A, Pánek T, Gałka M, et al. (2019) Landslides increased Holocene habitat diversity on a flysch bedrock in the Western Carpathians. *Quaternary Science Reviews* 219: 68–83.

Solon J, Borzyszkowski J, Bidłasik M, et al. (2018) Physico-geographical mesoregions of Poland: Verification and adjustment of boundaries on the basis of contemporary spatial data. *Geographia Polonica* 91(2): 143–170.

Tołpa S, Jasnowski M and Pałczyński A (1967) System genetyczny klasyfikacji torfów występujących w złożach Europy Środkowej. *Zeszyty Problemowe Postępów Nauk Rolniczych* 76: 27–99.

Tomczyk AM and Bednorz E (eds) (2022) *Atlas Klimatu Polski (1991-2020)*. Poznań: Bogucki Wydawnictwo Naukowe.

Zarzycki K (2002) *Ecological Indicator Values of Vascular Plants of Poland*. Kraków: Polish Academy of Sciences, W Szafer Institute of Botany.

Table 1. Results of radiocarbon dating of the Klaklowo and Kotoń landslide fen sediments. * – MKL: Laboratory of Absolute Dating in Kraków, Poland, in collaboration with the Center For Applied Isotope Studies, University of Georgia, U.S.A.; Beta Analytic, Inc. Miami, Florida, U.S.A. Calibration done in OxCal v4.4.4 Bronk Ramsey (2021) with IntCal20 calibration curve (Reimer et al., 2020). Selection and taxa determination of plant macrofossils for AMS dating was conducted by [details omitted for double-anonymized peer review].

No	Depth (cm)	Material (macrofossil type)	Lab code*	Age ¹⁴ C (BP)	Calibrated age 2σ 95.4% (cal BP)	Mean μ (cal BP)	Sigma σ (cal years)	Context of dating
Klaklowo landslide fen								
1	70–72.5	<i>Pinus sylvestris</i> needle, <i>Betula pubescens</i> fruits and fruit scales, <i>Scirpus sylvaticus</i> fruits and seeds, <i>Sambucus racemosa</i>	MKL- A6646	9025 ± 28	10,240– 10,179 (95,4%)	10,208	25	Above the supposed hiatus

1									
2									
3			fruits, <i>Rubus</i>						
4			<i>idaeus</i> seeds						
5									
6						11235-			
7						11098			
8			<i>Pinus</i>			(94,6%),			Below the
9	2	85–87.5	<i>sylvestris</i>	MKL-	9726 ± 30	10913-	11,167	58	supposed
10			needles	A6592		10904			hiatus
11						(0,8%)			
12									
13									
14									
15						11,390–			
16						11,379			Within the
17			<i>Larix</i>			(1.9%),			Younger
18	3	140–142.5	<i>decidua</i>	MKL-	9860 ± 33	11,326–	11,261	38	Dryas
19			needles	A6288		11,202			chronozone
20						(93.6%)			
21									
22									
23						12,479–			
24						12,096			Allerød and
25			<i>Pinus</i>			(92.9%),			Younger
26	4	160–162.5	<i>sylvestris</i>	MKL-	10,395 ± 30	12,086–	12,279	119	Dryas
27			needles	A6289		12,058			boundary
28						(2.6%)			
29									
30									
31									
32			<i>Pinus</i>			13,092–			
33	5	200–202.5	<i>sylvestris</i>	MKL-	11,080 ± 29	12,918	13,009	52	Gerzensee
34			needles	A6290		(95.4%)			oscillation
35									
36									
37									
38									
39									
40									
41									
42									
43									
44									
45									
46									

1									
2									
3									
4	6	239.5–241.5	<i>Pinus sylvestris</i> needles	MKL-A6291	11,678 ± 30	13,596–13,475 (95.4%)	13,539	37	Allerød-1 and Allerød-2 boundary
5									
6									
7									
8									Beginning
9									of
10	7	260–262.5	<i>Pinus sylvestris</i> needles	MKL-A6130	11,700 ± 31	13,604–13,481 (95.4%)	13,549	39	accumulatio
11									n of peat
12									sequence
13									
14									
15									
16									Beginning
17									of
18	8	262.5–265	Stems of mosses	MKL-A5610	12,253 ± 37	14,761–14,746 (0.8%)	14,190	127	accumulatio
19									n of peat
20									sequence
21									
22									
23									
24									Beginning
25									of
26	9	270–272.5	<i>Pinus sylvestris</i> needles, stems of mosses	MKL-A5462	13,353 ± 37	16,228–15,906 (95.4%)	16,068	79	accumulatio
27									n of peat
28									sequence
29									
30									
31									
32									Centre of
33									the second
34	10	319–322.5	<i>Eleocharis palustris</i> fruits, stems of mosses	MKL-A5463	11,981 ± 35	14,024–13,906 (48.2%), 13,894–13,785 (47.2%)	13,898	75	organic horizon
35									
36									
37									
38									
39									
40									
41									
42									
43									
44									
45									
46									

1										
2										
3										
4	11	347.5–350	Stems of	MKL-	12,238 ± 34	14,309–	14,160	100	Top of the	
5			mosses	A5464		14,059			first organic	
6						(95.4%)			horizon	
7										
8										
9	12	355–357.5	Stems of	MKL-	12,422 ± 42	14,896–	14,568	176	Bottom of	
10			mosses	A5465		14,277			the first	
11						(95.4%)			organic	
12									horizon	
13	Kotoń landslide fen									
14										
15										
16			<i>Sambucus</i>							
17	13	77.5–80	<i>racemosa</i>	MKL-	6805 ± 28	7682–7587	7639	26	Minerogenic	
18			fruits, <i>Rubus</i>	A6645		(95.4%)			cover	
19			<i>idaeus</i> seeds							
20										
21										
22						11,935–				
23						11,698				
24			<i>Carex</i>			(92.9%),				
25	14	180–182.5	<i>rostrata</i>	MKL-	10,159 ± 31	11,665–	11,804	72	Sedge-moss	
26			fruits	A6591		11,650			fen peat	
27						(2.5%)				
28										
29										
30										
31			<i>Pinus</i>			13,226–				
32			<i>sylvestris</i>			13,218				
33			needles,			(1.4%),				
34	15	262.5–265	leaves	MKL-	11,242 ± 34	13,180–	13,140	28	Moss fen	
35			fragments	A6590		13,093			peat	
36			(not			(94.0%)				
37			identified)							
38										
39										
40										
41										
42										
43										
44										
45										
46										

16	325–327.5	<i>Carex rostrata</i> fruits	MKL-A6589	11,967 ± 33	14,021–13,914 (45.8%), 13,884–13,766 (49.6%)	13,890	80	Moss fen peat/ Alder peat
17	390–392.5	<i>Alchemilla</i> sp. fruits, <i>Carex rostrata</i> fruits, <i>Valeriana simplicifolia</i> / <i>dioica</i> fruits, Poaceae fruit	MKL-A6588	11,981 ± 33	14,023–13,906 (48.3%), 13,892–13,785 (47.1%)	13,899	75	Organic-minerogenic sediment
18	431–435	<i>Alchemilla</i> sp. fruits, <i>Carex rostrata</i> fruit, <i>Carex</i> sp. trigonus fruit	Beta-692394	12,300 ± 40	14,440–14,083 (83.5%), 14,805–14,710 (12.0%)	14,302	195	Horizon with numerous macrofossils within silt sequence

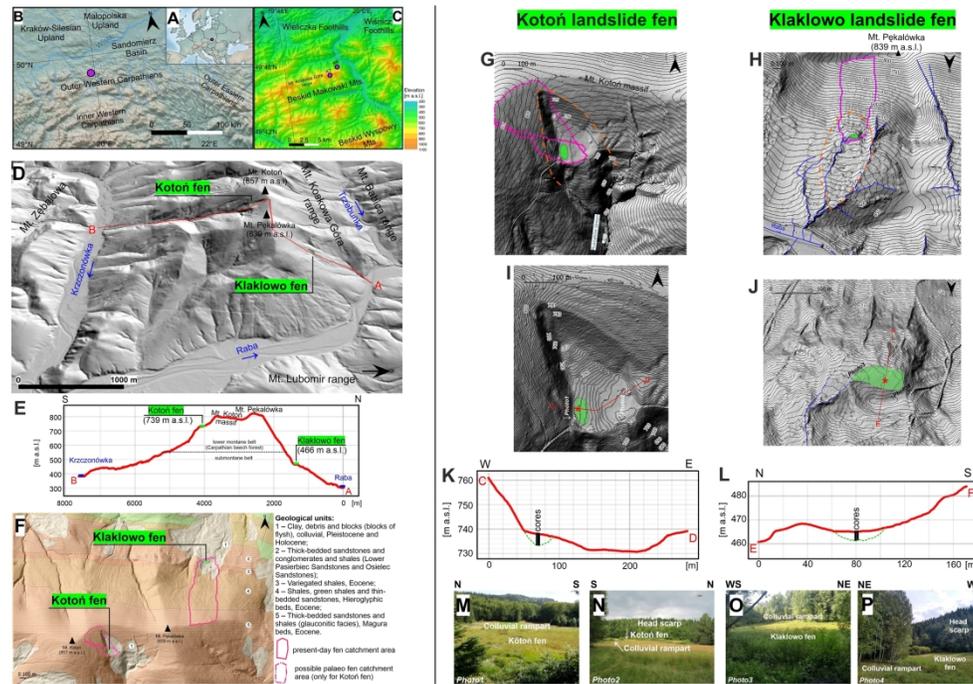


Figure 1. Location of the study area (purple circle) in Europe (A) and in the region of the Outer Western Carpathian (B); C) location of the Kotoń (KT) and the Klakłowo (KK) landslide fens (purple circles) in the Beskid Makowski Mountains; D) digital terrain model (DTM) of the Mt. Koskowa Góra range with culminations of Mt. Pękalówka and Mt. Kotoń, with the Kotoń and Klakłowo landslide fens embedded within their slopes and with the projection line of the A-B cross section; E) the A-B cross section cutting through the Mt. Koskowa Góra range and the Kotoń and Klakłowo landslide fen areas; F) DTM draped with geological map (Książkiewicz et al. 2016, <https://cbdgmapi.pgi.gov.pl/arcgis/services/kartografia/smgp50k/MapServer/WMServer>, see the numbers in the figure and legend for the geological units descriptions) showing the Kotoń and Klakłowo landslide zones (extent of geological unit 1) with the position of the landslide fens (areas in green) and their present-day catchment areas (for the Kotoń fen also possible palaeo fen catchment); G) and H) DTMs of the Kotoń and Klakłowo landslide zones (delineated with orange dot-dash line) with the position of the landslide fens (area in green) and their present-day catchment areas (pink solid line) (for Kotoń fen also possible palaeo fen catchment - dot-dash line); I) and J) DTMs with the present-day landslide sub-scarp areas around the Kotoń and Klakłowo fens (in green), projection lines of the C-D and E-F cross-sections and drilling sites (red stars); K) and L) C-D and E-F cross-sections through the Kotoń and Klakłowo fens with the position of the cores' drilling sites; M), N), O) and P) present-day Kotoń and Klakłowo fens areas (photos M and N by [details omitted for double-anonymized peer review], photos O and P by [details omitted for double-anonymized peer review]). Sources of basemaps: A) <https://www.naturalearthdata.com/downloads/10m-cross-blend-hypso/cross-blended-hypso-with-relief-water-drains-and-ocean-bottom/>); B) DTM from <https://download.gebco.net/> draped with the basemap of the part A); part C, D, F, G, H, I and J) DTM from WCS service <https://mapy.geoportal.gov.pl/wss/service/PZGIK/NMT/GRID1/WCS/DigitalTerrainModelFormatTIFF>.

241x170mm (300 x 300 DPI)

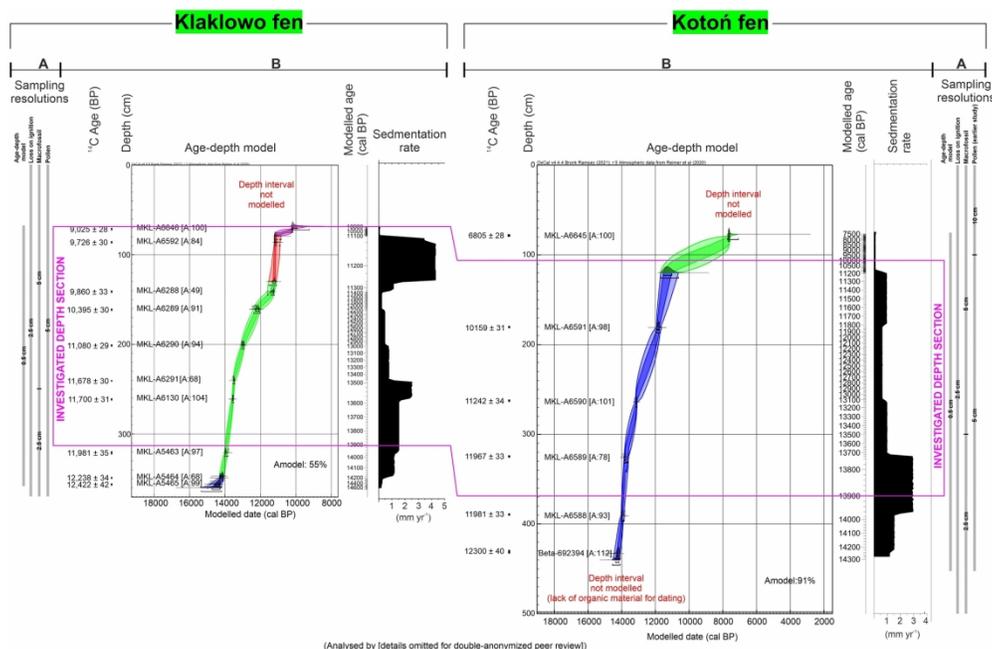


Figure 2. Comparison of sampling resolutions of methods and results of radiocarbon dating between Klaklowo and Kotoń fens. Mirrored order for both sites: A) comparison of sampling resolutions of multi-proxy analyses applied in this study; B) uncalibrated 14C age obtained for sampled depths (see Table 1), age-depth models, modelled age scales and sedimentation rates derived from age-depth models. Investigated depth section (pink rectangle) – depth/time interval analysed in the current paper.

200x130mm (300 x 300 DPI)

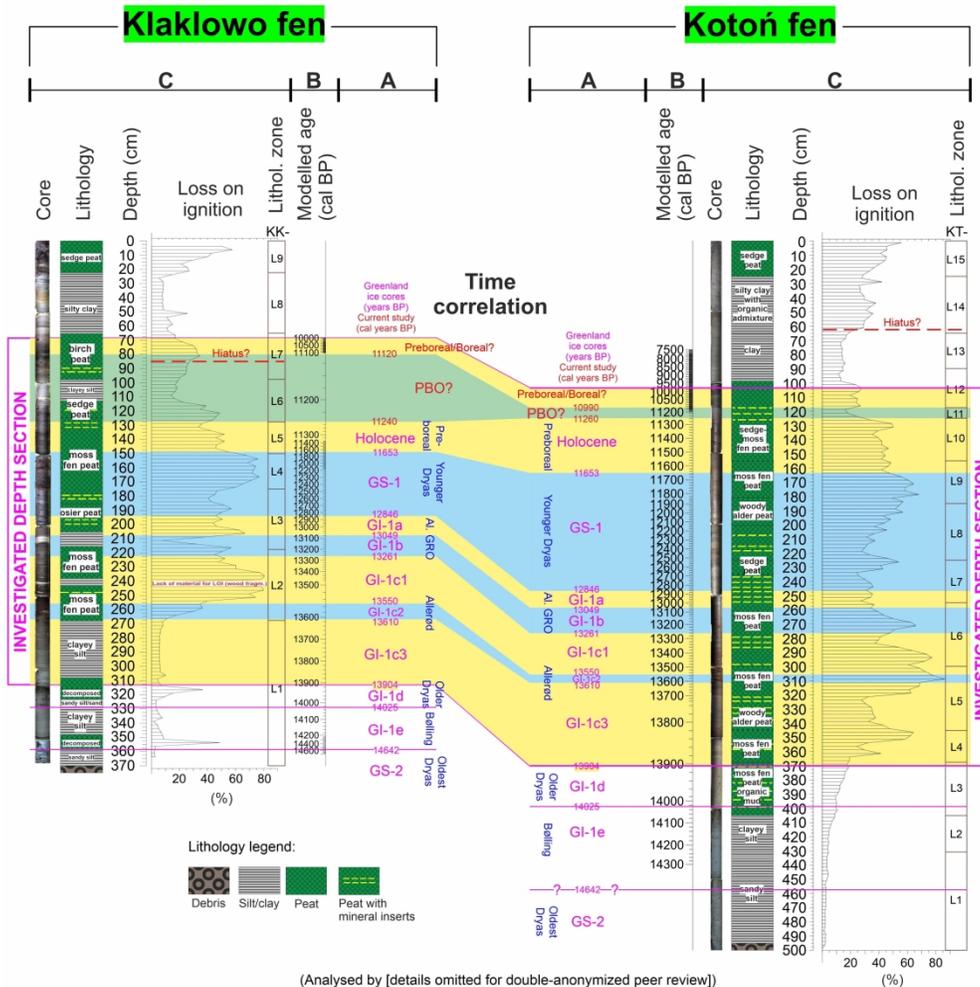


Figure 3. Comparison of lithological data between Klaklowo and Kotoń fens. Mirrored order for both sites: A) Greenland ice cores event stratigraphy and corresponding traditional stratigraphic division (in blue), GRO – Gerzensee oscillation, Al. – Allerød, PBO – the supposed Preboreal oscillation; B) modelled age scales derived from age-depth models; C) lithological data: core photo, lithological column, loss on ignition curve and interpreted lithological zones (lithol. zone). In the background: climatic oscillations according Greenland ice cores event stratigraphy (Rasmussen et al. 2014) (pale yellow – warming, pale blue – cooling, pale green – presumably cooling). Investigated depth section (pink rectangle) – depth/time interval analysed in the current paper.

126x126mm (600 x 600 DPI)

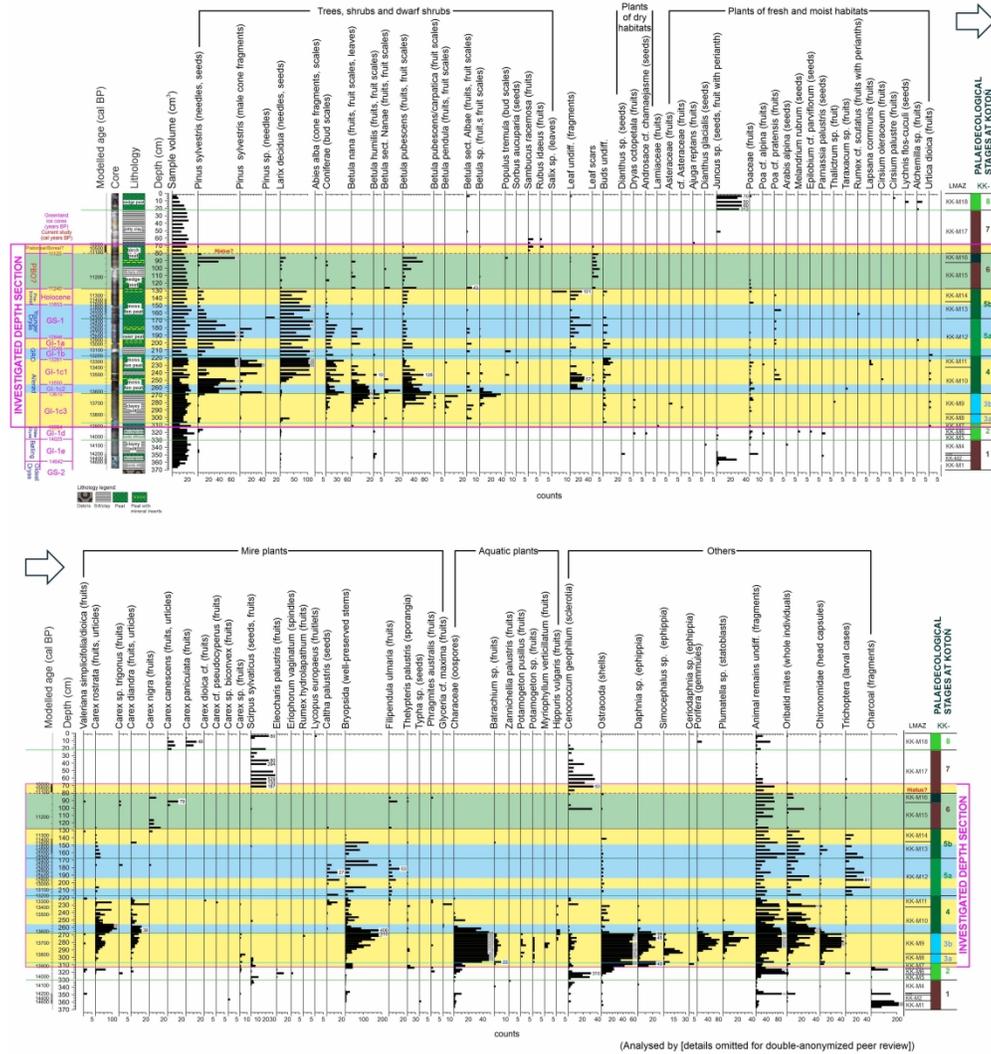


Figure 4. Macrofossil diagram of the Klaklowo landslide fen deposits divided into LMAZ and palaeoecological stages of development and compared with Greenland ice cores event stratigraphy and corresponding traditional stratigraphic division (in blue), GRO – Gerzensee oscillation, AI. – Allerød, PBO – the supposed Preboreal oscillation. In the background: climatic oscillations according to Greenland ice cores event stratigraphy (Rasmussen et al. 2014) (pale yellow – warming, pale blue – cooling, pale green – presumably cooling). See SM Table S5 for detailed description of the LMAZ. Values are absolute counts per sample (sample volumes presented on the left). Investigated depth section (pink rectangle) – depth/time interval analysed in the current paper.

163x173mm (600 x 600 DPI)

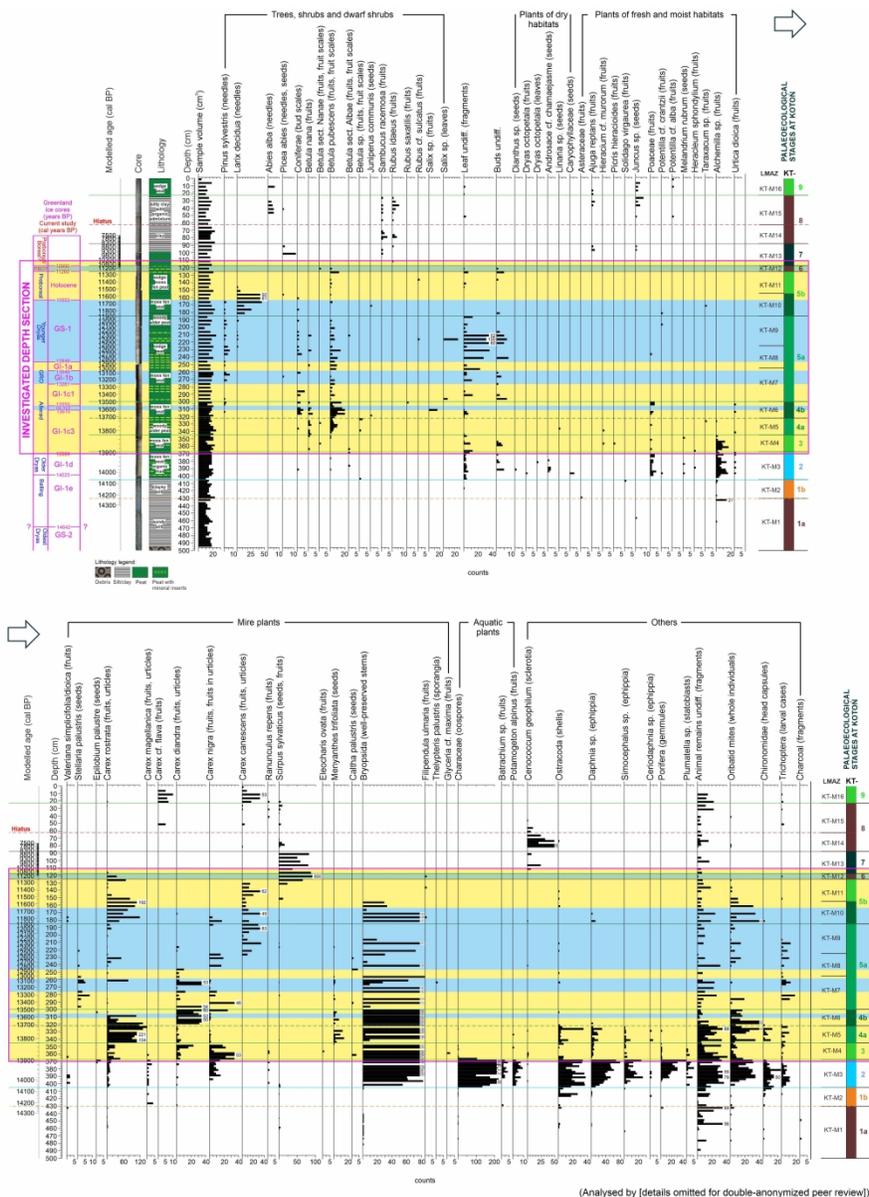


Figure 5. Macrofossil diagram of the Kotoń landslide fen deposits divided into LMAZ and palaeoecological stages of development and compared with Greenland ice cores event stratigraphy and corresponding traditional stratigraphic division (in blue), GRO – Gerzensee oscillation, AI. – Allerød, PBO – the supposed Preboreal oscillation. In the background: climatic oscillations according to Greenland ice cores event stratigraphy (Rasmussen et al. 2014) (pale yellow – warming, pale blue – cooling, pale green – presumably cooling). See SM Table S6 for detailed description of the LMAZ. Values are absolute counts per sample (sample volumes presented on the left). Investigated depth section (pink rectangle) – depth/time interval analysed in the current paper.

179x239mm (600 x 600 DPI)

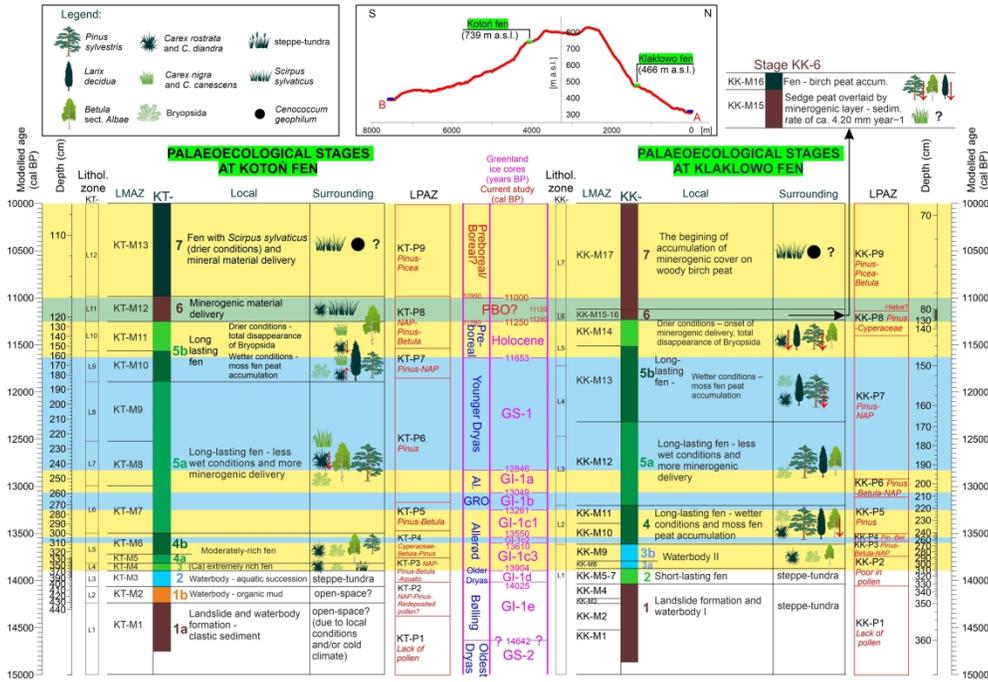


Figure 6. Summary diagram in time domain presenting comparison of the stages of the palaeoecological (local and surrounding) development, lithological zones (lithol. zone), LMAZ, LPAZ between Kotoń and Klakłowo landslide fens. Data are compared with Greenland ice cores event stratigraphy and corresponding traditional stratigraphic division (in blue), GRO – Gerzensee oscillation, Al. – Allerød, PBO – the supposed Preboreal oscillation. In the background: climatic oscillations according to Greenland ice cores event stratigraphy (Rasmussen et al. 2014) (pale yellow – warming, pale blue – cooling, pale green – presumably cooling).

210x144mm (600 x 600 DPI)

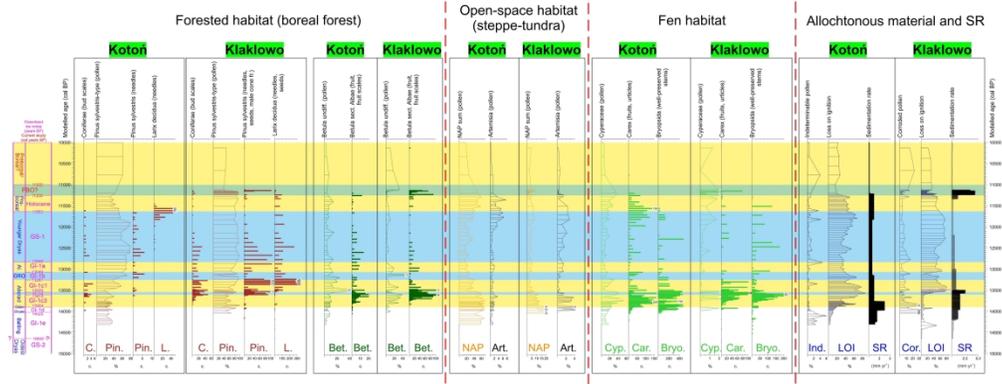


Figure 7. Summary diagram in time domain presenting comparison of the representative plant taxa and other proxies between Kotoń and Klakłowo landslide fens. Data are compared with Greenland ice cores event stratigraphy and corresponding traditional stratigraphic division (in blue), GRO – Gerzensee oscillation, AI – Allerød, PBO – the supposed Preboreal oscillation. In the background: climatic oscillations according to Greenland ice cores event stratigraphy (Rasmussen et al. 2014) (pale yellow – warming, pale blue – cooling, pale green – presumably cooling). Plant taxa abbreviations: C. – Coniferae; Pin. – *Pinus sylvestris*-type (pollen) or *Pinus sylvestris* (macrofossils); L. – *Larix decidua*; Bet. – *Betula udiff.* (pollen) or *Betula sect. Albae* (macrofossils); NAP – non-arboreal pollen; Art. – *Artemisia*; Cyp. – *Cyperaceae*; Car. – *Carex*; Bryo. – *Bryopsida*; Ind. – indeterminate pollen; LOI – loss on ignition; SR – sedimentation rate; Cor. – corroded pollen.

467x184mm (300 x 300 DPI)

1
2
3 1 Supplemental Material to the paper:
4
5

6 2 [details omitted for double-anonymized peer review]
7
8

9 3
10

11 4 **Site description – additional information**

12 5 *Climate*

13
14
15
16 6 Temperature oscillation throughout the year reaches 21.0°C, whereas difference in
17
18 7 precipitation equals 80 mm (Climate Data, 2024). June is the warmest (mean: 18.1°C) and the
19
20 8 most rainy (mean: 140 mm) month, whereas January is the coldest (mean: -2.8 °C) and
21
22 9 February is the driest (mean: 60 mm). June is also the month with the highest number of
23
24 10 sunshine hours (mean: ca. 10.0 h/day), in opposite to January (mean: ca. 3.6 h/day) (years of
25
26 11 measurements: 1999 – 2019). Month of the lowest relative air humidity is April (70.1%), in
27
28 12 contrast to the highest values for November (84.9 %) (Climate Data, 2024).
29
30
31

32 13 33 34 14 *Landslides description*

35
36 15 The formation of the Kotoń landslide zone (ca. 250 m wide and ca. 700 m long, a central
37
38 16 point at ca. 730 m a.s.l.) was related to the development of the upper part of the Rusnaków
39
40 17 stream (valley head zone) (Figure 1 F and G). The landslide represents a type of rockslide,
41
42 18 translational, consequent-sliding landslide (Margielewski, 2001b) where the rock material has
43
44 19 been gravitationally displaced towards the inclination of the rock layers. Except for the lower
45
46 20 part of the landslide form reactivated by the erosional activity of Rusnaków stream, no
47
48 21 subsequent rejuvenations of the Kotoń landslide zone after its initial formation were observed.
49
50
51 22 The Klaklowo landslide zone is ca. 300 m wide and ca. 700 m long, a central point at ca. 450
52
53 23 m a.s.l.) possesses an amphitheatre shape (Figure 1 F and H) and it represents a type of
54
55 24 multiple rotational landslide which during its development underwent several rejuvenations
56
57 25 (Margielewski, 2001a).
58
59
60

26

27 *Soil and vegetation*

28 Two altitudinal-climatic vegetation belts are distinguished in the region of the Beskid
29 Makowski Mountains (Mirek 2013) (Figure 1 E): 1 - submontane (< 550 m a.s.l.), with the
30 colline form of the *Tilio-Carpinetum* association (the indicator forest community), and
31 nowadays overgrown by secondary grass-rich communities, *Arrhenatherion* alliance (the so-
32 called oak-hornbeam meadows), 2 - and the lower montane vegetation belt (550–900 m a.s.l.),
33 represented by *Dentario glandulosae-Fagetum* (the fertile Carpathian beech forest) and by
34 *Luzulo luzuloides-Fagetum* (the montane acidophilous beech forest) with *Polygono-Trisetion*
35 alliance (the secondary communities of seminatural meadows and pastures).

36

37 *Materials and methods – additional information***38 *Calculation of the solar irradiation***

39 For the Kotoń and Klakłowo fens' close surroundings, raster maps of global irradiation
40 (including beam, diffuse and ground reflected irradiation) and insolation time (duration of
41 beam irradiation expressed in hours per a given day) were calculated using GRASS GIS
42 r.sun.insoltime algorithm (GRASS Development Team, 2015) in QGIS 3.22.10 (QGIS
43 Development Team, 2021), in order to recognize the local differences in this parameter
44 between the sites which could affect the conditions for plant communities growth and, as a
45 consequence, composition of the deposited organic material. As an input data, the digital
46 terrain model (elevation, aspect, slope) from
47 <https://mapy.geoportal.gov.pl/wss/service/PZGIK/NMT/GRID1/WCS/DigitalTerrainModelFo>
48 rmatTIFF of the Beskid Makowski Mountains region was applied, and the daily sums of
49 irradiation and insolation time was computed for the specific days of the year (aimed to
50 represent four seasons): 1 January, 1 April, 1 June, 1 October (counted for the non-leap year).

1
2
3 51 Shadowing influence of relief, important in mountainous areas, was used by default.
4

5 52 Computation of irradiation sums for the whole month/season/year was not possible due to
6
7 53 processor limitations.
8
9

10 54

11
12 55 *Calculations of the fen catchment area*
13

14 56 Catchment area was delineated to recognize the local differences between the sites which
15
16 57 could affect the dynamics of minerogenic material delivery to the fens and resulting changes
17
18 58 in lithology of the fen sediments. GRASS GIS algorithms (r.fill.dir, r.watershed,
19
20 59 r.stream.extract, r.water.outlet) (GRASS Development Team, 2015) in QGIS 3.22.10 (QGIS
21
22 60 Development Team, 2021), were used for this purpose according to the tutorial delivered by
23
24 61 IHE Delft Institute for Water Education (2025). The main stages of the computations
25
26 62 consisted of creating a hydrologically correct DEM by filling the sinks, calculating flow
27
28 63 accumulation, delineating streams using a flow accumulation threshold and delineating a
29
30 64 catchment of a specified outlet (flow accumulation threshold was assumed as 500 cells to
31
32 65 delineate also small temporal water flows). In case of the more problematic Kotoń fen, the
33
34 66 delineation of the present-day catchment was done in the way that the outlet was positioned
35
36 67 on the temporal watercourse on the east beneath the colluvial rampart, because this
37
38 68 watercourse was more visible than other minor delineated water flows within the fen area
39
40 69 (Figure 1 G and I). Therefore, the obtained present-day catchment does not refer exactly to the
41
42 70 fen itself. Moreover, as the Kotoń fen depression exhibits N-S elongated shape, it is possible
43
44 71 that in the past the fen's depression was also fed by the water flows coming from a much
45
46 72 wider extent of the western scarp and slope, which presently seem to gather into temporal
47
48 73 stream omitting the elevated Kotoń fen from the north (Figure 1 G and I). Therefore, also this
49
50 74 part of the drainage system was taken into consideration and the possible palaeo catchment of
51
52 75 the fen was delineated. Outlet of the Klaklowo fen catchment was positioned slightly beneath
53
54
55
56
57
58
59
60

1
2
3 76 the present-day fen itself (on the main stream draining the fen) also accounting for possible
4
5 77 palaeo extent of the Klaklowo fen drainage basin.
6
7
8 78

9
10 79 ***Radiocarbon dating and age-depth model***
11

12 80 In case of the Kotoń fen, below the depth of 440 cm the amount of plant macrofossil was too
13
14 81 small for AMS dating. For both Klaklowo and Kotoń sites, the depth section above 68 cm and
15
16
17 82 77 cm, respectively, was not the goal of the presented study (sediments younger than late
18
19 83 glacial and early Holocene) (Figure 2 B).
20

21 84 Eighteen radiocarbon dates were acquired in total: 12 for Klaklowo fen and 6 for
22
23 85 Kotoń fen deposits. One sample with the lowest weight from the Kotoń site (sample depth
24
25 86 435–431 cm, Beta-692394) was dated in Beta Analytic, Inc. Miami, Florida, U.S.A, whereas
26
27 87 the remaining seventeen samples were dated in the Laboratory of Absolute Dating in Kraków,
28
29 88 Poland, in collaboration with the Center For Applied Isotope Studies, University of Georgia,
30
31 89 U.S.A.. In case of the Klaklowo fen, two radiocarbon dates aiming to date the beginning of
32
33 90 the accumulation of the peat sequence at a depth of approximately 260–270 cm (MKL-A5610
34
35 91 and MKL-A5462) were not included in the calculations due to their overestimated ages.
36
37
38
39

40 92 In the construction of the age-depth models for both sites the *Boundary command* was
41
42 93 applied at depths of distinctive changes recorded in the lithological and/or biotic proxies. For
43
44 94 Kotoń fen it was a boundary at a depth of 120 cm, reflecting the decrease in loss on ignition
45
46 95 curve and disappearance of many plant taxa registered in macrofossil data. Based on similar
47
48 96 observations, for the Klaklowo fen *Boundary command* was introduced at a depth of 130 cm.
49
50 97 Additionally, for the Klaklowo fen, the boundary was also introduced at 347 cm (organic
51
52 98 horizon) and 79 cm (a significant change in macrofossils and pollen assemblages).
53
54
55

56 99
57
58 100 ***Plant macrofossil analysis***
59
60

1
2
3 101 Plant macrofossils analysis was performed using various keys and publications (Aalto,
4
5 102 1970; Anderberg, 1994; Berggren, 1969, 1981; Birks, 2013; Cappers et al., 2012; Kats et al.,
6
7 103 1965; Körber-Grohne, 1964, 1991; Kowalewski, 2014; Mauquoy and van Geel, 2007;
8
9 104 Velichkevich and Zastawniak, 2006, 2008). Determined plant and animal taxa were grouped
10
11 105 in the following manner: trees, shrubs and dwarf shrubs were placed together, whereas other
12
13 106 vascular plants, Bryopsida and Characeae were divided according to the degree of habitat
14
15 107 wetness (dry, fresh and moist, mire and aquatic). Taxa of animal and other remains were
16
17 108 assigned to the group 'Others'.
18
19
20
21
22

23 110 ***Pollen and non-pollen palynomorphs (NPPs) analysis***

24
25
26 111 For the Klaklowo sediment sequence (367–0 cm), each sample (approximately 1 cm³ of
27
28 112 sediment volume) was taken at 5 cm interval and underwent a standard chemical preparation
29
30 113 for palynological analysis (Erdtman, 1960; Fægri and Iversen, 1989). Quantitative analysis of
31
32 114 pollen and NPPs (using *Lycopodium* tablets) consisted of counting (under a light microscope)
33
34 115 pollen grains of trees and shrubs up to at least 600 per sample. Pollen taxonomic
35
36 116 determination was based on the reference collection of the modern pollen slides and on keys
37
38 117 and atlases (Beug, 2004; Moore et al., 1991; Reille, 1992). Non-pollen palynomorphs were
39
40 118 identified according to Van Geel (1978) and Van Geel et al. (1980, 2003, 2007).
41
42
43

44 119 Also in this paper we use the previous pollen dataset of the Kotoń landslide fen
45
46 120 (Margielewski, 2001b; Margielewski et al., 2003), however the pollen percentages
47
48 121 calculations and interpretation of the local pollen assemblage zones were performed again to
49
50 122 make it more comparable with the current pollen analysis results obtained for the Klaklowo
51
52 123 fen. In the archival pollen dataset from Kotoń (450–0 cm), sampling interval equalled ca. 10
53
54 124 cm for the depth section of 100–0 cm, whereas below 100 cm (for the late glacial deposits),
55
56 125 sampling interval was smaller, mostly ca. 5 cm (however at some depths there were changes
57
58
59
60

1
2
3 126 from this regularity). Samples preparation was conducted based on the modified method of
4
5 127 Erdtman's acetolysis (Erdtman, 1943). Quantitative analysis of pollen (using *Lycopodium*
6
7 128 tablets) consisted of counting (under a light microscope) pollen grains of trees and shrubs up
8
9
10 129 to at least 500 per sample, except for the Holocene deposits, in which grains were counted to
11
12 130 at least 1000. As the archival pollen dataset of Kotoń (450–0 cm) did not cover the whole
13
14 131 length of the sediment core drilled in the current study (500 cm), the bottommost 0.5 m
15
16 132 interval of the currently obtained Kotoń core were subjected to pollen analysis (in the same
17
18 133 manner as the current Klaklowo sediment core) in order to supplement this gap in the pollen
19
20 134 sequence.

21
22
23
24 135 It is important to stress, that for both investigated sites, there was a total or significant
25
26 136 depletion in pollen grains in the bottommost minerogenic deposits. For the Klaklowo fen, in
27
28 137 the 367–332.5 cm depth interval the lack of pollen grains was determined, whereas the depth
29
30 138 interval of 332.5–302.5 cm was poor in pollen. For the Kotoń fen, the supplementary analysis
31
32 139 of the bottommost 0.5 m of sediments also revealed a total lack of pollen grains. Some
33
34 140 explanation of this phenomenon can be found in Pilch et al. (2025b).

35
36
37 141

38 142 **Results**

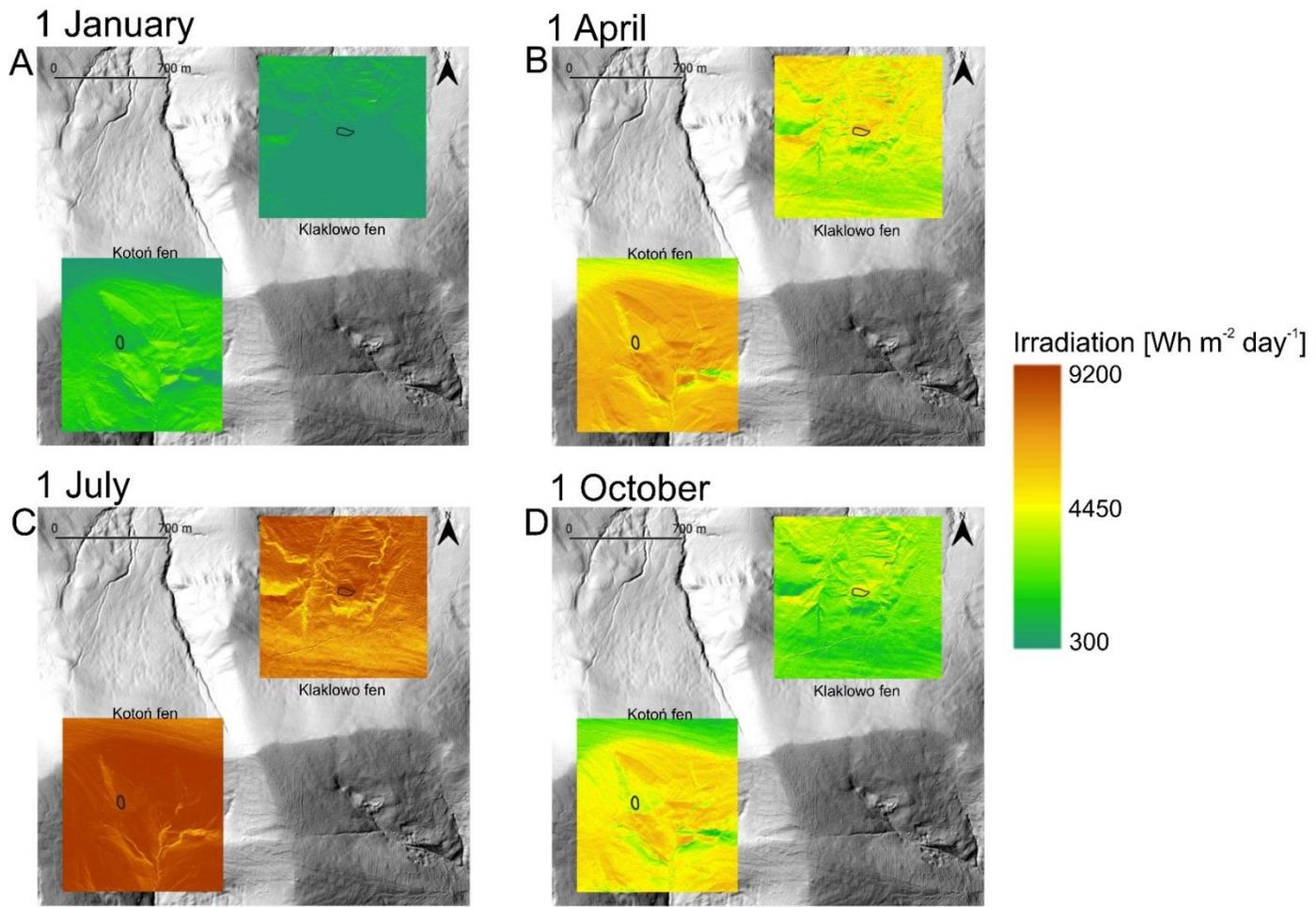
39 143 ***Results of the solar irradiation calculations***

40
41
42 144 For the examined 1st days of April, July and October, Kotoń and Klaklowo fens (areas within
43
44 145 fen boundaries) receive a similar amount of mean irradiation (beam, diffuse and ground
45
46 146 reflected): 5764 and 5563, 8864 and 8741, 4373 and 4082 Wh m⁻² day⁻¹, respectively, and
47
48 147 exhibit a similar (beam) insolation time: 12, 15 and 16, 11 h, respectively (Supplemental
49
50 148 Material - SM Table S1, Figure S1 and Figure S2, parts B, C and D). The difference can be
51
52 149 found in amount of irradiation reaching both sites in winter (1st January): for the Kotoń fen
53
54 150 the mean irradiation yields 1339 Wh m⁻² day⁻¹ (8 h of insolation time), whereas for the
55
56
57
58
59
60

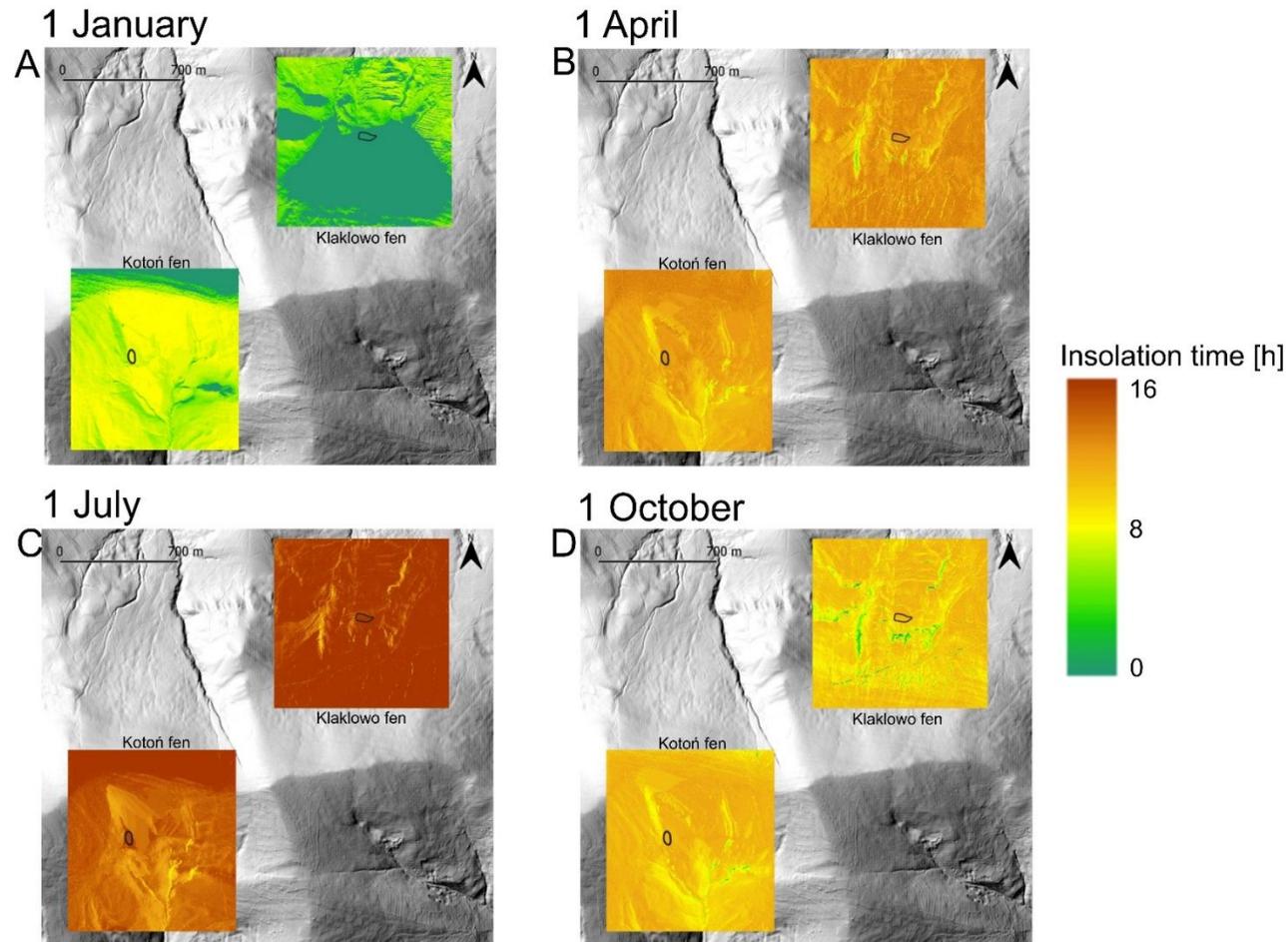
1
2
3 151 Klaklowo fen it amounts to 397 Wh m⁻² day⁻¹ (0 h of insolation time) (SM Table S1, Figure
4
5 152 S1 and Figure S2, part A). As the mean irradiation values in SM Table S1 are given for the
6
7 153 area within fens boundaries, it is important to stress that the other areas close of the fen (e.g.
8
9 154 steep slopes and head scarps, shaded gullies) could exhibit differing irradiation values, and
10
11 155 consequently also the habitat conditions for vegetation growth could be spatially diversified
12
13 156 around the fens (SM Figure S1 and Figure S2).
14
15
16
17 157
18
19 158 **Table S1.** Results of the solar irradiation calculations for the Kotoń and Klaklowo landslide
20
21 159 fens (only within the fen boundaries, see black solid line in SM Figure S1 and Figure S2).
22
23

	1 st January	1 st April	1 st July	1 st October
Mean irradiation (Wh m ⁻² day ⁻¹)				
Kotoń	1339	5764	8864	4373
Klaklowo	397	5563	8741	4082
Mean insolation time /Duration of beam (direct) irradiation (h)				
Kotoń	8	12	15	11
Klaklowo	0	12	16	11

1
2
3 161 **Figure S1.** Maps of daily sums of global irradiation (beam, diffuse and ground reflected) for the Kotoń and Klaklowo fens and surrounding
4
5 162 areas. Black solid line – fen boundaries.
6
7



1
2
3 164 **Figure S2.** Maps of daily sums of insolation time (duration of beam irradiation) for the Kotoń and Klaklowo fens and surrounding areas. Black
4
5 165 solid line – fen boundaries.
6
7



1
2
3 167 ***Results of the catchment area calculations***
4

5 168 Delineated catchments for both the Kotoń and Klaklowo fens differ substantially in term of
6
7 169 area, shape, relief and bedrock geology. Area of the Klaklowo fen drainage basin account for
8
9 170 ca. 325 912 m², and it is ca. 3 times greater than the area of the Kotoń possible palaeo
10
11 171 catchment (104 563 m²) and ca. 12 times greater than the present-day catchment (28 004 m²)
12
13 172 (SM Table S2). Klaklowo fen catchment has an elongated shape and spans from the crest of
14
15 173 the Mt. Pękalówka downward the slope and encompasses the whole semicircular head scarp
16
17 174 of the Klaklowo landslide (maximum ca. 550 m of denivelation, Figure 1 H). This implies the
18
19 175 possible inflow of water with organic and minerogenic material uniformly from all directions
20
21 176 around the fen. In case of both possible palaeo and the present-day Kotoń fen catchments,
22
23 177 flow of water drains only the western part of the Kotoń landslide (Figure 1 G). The present-
24
25 178 day catchment includes only a narrow belt spanning downward the slope of the Mt. Kotoń,
26
27 179 and some part of the western head scarp (ca. 100 m of denivelation, Figure 1 G). The possible
28
29 180 palaeo catchment covers the area of the present-day catchment and the area above it: a vast
30
31 181 part of the Mt. Kotoń slope (reaching the crest), the entire area of the western head scarp and
32
33 182 some part of the sub-scarp flattening (also ca. 100 m of denivelation, Figure 1 G). In term of
34
35 183 the bedrock geology, the Kotoń fen catchment drains the area entirely built of thick-bedded
36
37 184 sandstones and shales (glauconitic facies) of Magura beds (Figure 1 F). Klaklowo catchment
38
39 185 bedrock is more diverse and includes (from the mountain crest) Magura beds and shales,
40
41 186 green shales and thin-bedded sandstones of Hieroglyphic beds, as well as possibly it reaches
42
43 187 the extent of variegated shales and thick-bedded sandstones and conglomerates and shales of
44
45 188 Lower Pasierbiec Sandstones and Osielec Sandstones (Figure 1 F).
46
47
48
49
50
51
52
53

54 189
55
56 190 **Table S2.** Results of the catchment area calculations for the Kotoń and Klaklowo landslide
57
58 191 fens
59
60

	Kotoń fen present-day catchment	Kotoń fen possible palaeo-catchment	Klaklowo present-day catchment
Area (m ²)	28 004	104 563	325 912

192

For Peer Review

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46

193 **Loss on ignition and peat type**

194 **Table S3.** Detailed description of the sediment, loss on ignition (LOI) and plant tissue data (peat type) of the Klaklowo fen deposits. The latter is
195 adopted from the earlier studies of the Klaklowo fen (Margielewski, 2001a).

Depth interval of lithological zone	Mineral and organic sediment type and loss on ignition (LOI) results
KK-L1 367–267.5 cm	<p>This interval is characterized by minerogenic sediment (clayey silt and sandy silt) yielding the low values in the loss on ignition curve (< 10%).</p> <p>At a depth of 357.5–347.5 cm an insert of decomposed peat (strongly humified) with <i>Bryales</i> sp. and wood, yields rise in LOI curve to ca. 45%. At a depth of 315–322.5 cm there is another horizon of decomposed peat, strongly humified, with <i>Carex</i> sp., <i>Bryales</i> sp. and <i>Betula</i> sp., resulting in LOI values increase to ca. 35%.</p>
KK-L2 267.5–217.5 cm	<p>This zone is represented by organic deposits: moss fen peat (<i>Parvo-Caricioni bryaleti</i>) dominated by <i>Bryales</i> pl. sp. (80%) and secondarily by <i>Phragmites australis</i>.</p> <p>LOI values grow from around 10% at 262.5 cm depth to around 60–80% at 250 cm depth. In the depth section of 250–232 cm LOI curve shows values of ca. 80%, maximum for the entire Klaklowo sequence. Between 232 and 217.5 cm, LOI curve shows noticeably lower values, ca. 40–60%, resulting from an admixture of minerogenic material.</p> <p>At a depth of 240–242.5 cm a piece of wood was found and preserved for future analysis – due to that no material for LOI was available.</p>
KK-L3 217.5–175 cm	<p>This interval begins with a noticeable minerogenic insert resulting in a drop to ca. 7% on the LOI curve between 217.5 and 207.5 cm.</p> <p>Above this horizon, at the depth section of 207.5–190 cm, woody osier peat (<i>Alnioni saliceti</i>) occurs, dominated by <i>Salix cinerea et aurita</i> (60%) and secondarily by <i>Bryales</i> pl. sp., <i>Carex</i> pl. sp. and <i>Calamagrostis</i> sp. LOI curve shows values of ca. 45–65%, resulting from the peat accumulation and admixture of minerogenic material.</p> <p>At the depth interval of 190–175 cm, organic accumulation continues again in a form of moss fen peat (<i>Parvo-Caricioni bryaleti</i>), dominated by <i>Bryales</i> pl. sp (90%) including <i>Calliargon giganteum</i>, <i>Drepanocladus</i> sp., <i>Mnium</i></p>

	sp. and secondarily by <i>Carex</i> sp. In the LOI curve values ca. 45–60% continuously reflect admixture of mineral material.
KK-L4 175–150 cm	This interval is represented by pure moss fen peat (<i>Parvo-Caricioni bryaleti</i>), dominated by <i>Bryales</i> pl. sp. and with reduced contamination by minerogenic matter. This is expressed in LOI curve showing high values, up to ca. 75 %.
KK-L5 150–127.5 cm	In this zone, moss fen peat (<i>Parvo-Caricioni bryaleti</i>) dominated by <i>Bryales</i> pl. sp. (60%) and secondarily by <i>Carex gracilis</i> and <i>Carex</i> sp. (30%) occurs. On the LOI curve a gradual decrease from ca. 55% to ca. 35% can be noticed, reflecting an increasing minerogenic delivery.
KK-L6 127.5–97.5 cm	Between 127.5 and 112.5 cm sedge peat (<i>Magno-Caricioni cariceti</i>) composed of <i>Phragmites australis</i> , <i>Carex</i> pl. sp., <i>Equisetum</i> sp. and wood (<i>Betula</i> , <i>Salix</i>) was determined. It is expressed in the LOI data as a peak of maximum 50%, which further decreases to ca. 30%. In the upper part of this interval (112.5–97.5) a minerogenic insert (clayey silt) appears resulting in a drop to ca. 15% on LOI curve.
KK-L7 97.5–65 cm	The deposits of this zone are composed of woody birch peat (<i>Betulioni betuleti</i>) dominated by <i>Betula</i> sp. (bark and wood, 60%) and secondarily by <i>Pinus</i> (bark), <i>Bryales</i> sp., <i>Carex</i> sp and other undefined material. The contamination of minerogenic material in this zone decreases between depths 97.5 and 80 cm (values on LOI curve grow from around 20% to ca. 30%), whereas from the depth 80 to 65 cm increases (values on LOI curve show maximum around 35% and later diminishes to ca. 20%).
KK-L8 65–22.5 cm	This zone is represented by minerogenic material (mostly silty clay) yielding low values (ca. 8%) on the LOI curve. At a depth of 50–52.5 (one sample) an increase to ca. 25% can be noticed.
KK-L9 22.5–0 cm	The uppermost layer of the Klaklowo sediment sequence consists of sedge peat (<i>Magno-Caricioni cariceti</i>), composed of <i>Carex</i> sp., <i>Carex rostrata</i> and <i>Phragmites australis</i> , resulting in a gradual increase of LOI value from 20 to 57%.

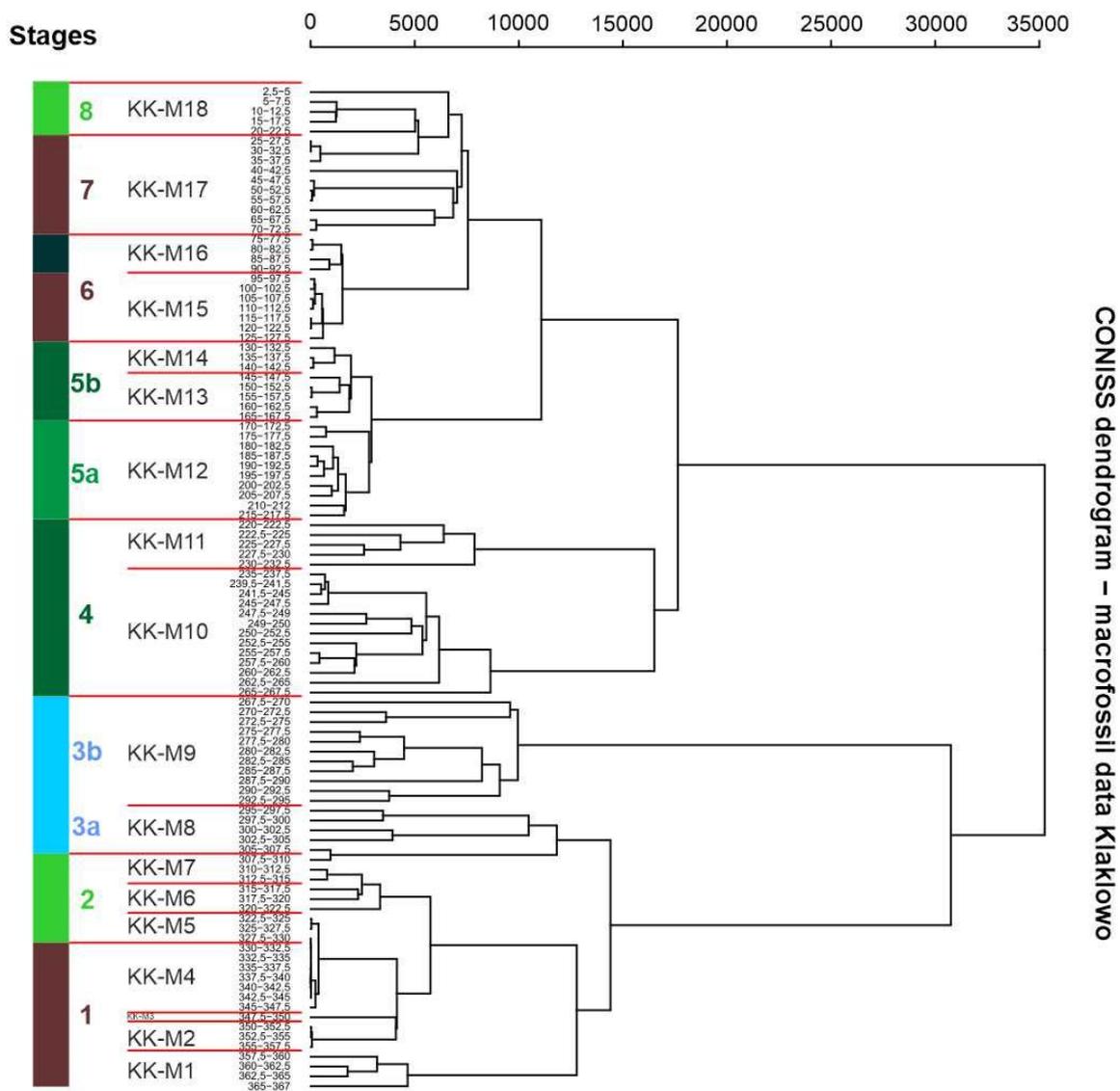
197 **Table S4.** Detailed description of the sediment, loss on ignition (LOI) and plant tissue data (peat type) of the Kotoń fen deposits. The latter is
 198 adopted from earlier studies of the Kotoń fen (Margielewski, 2001b; Margielewski et al., 2003).

Depth interval of lithological zone	Mineral and organic sediment type and loss on ignition (LOI) results
KT-L1 500–431 cm	This interval is characterized by occurrence of minerogenic sediment, silt with sand and debris admixture, showing low values of LOI <5%.
KT-L2 431–405 cm	Sediment of this interval consists of a clayey silt with an increasing content of organic matter (5–8%).
KT-L3 405–367.5 cm	Mineral material (silt) still prevails in the sediment of this zone; however, the share of organic matter continues to increase upward (10–20%).
KT-L4 367.5–345 cm	In this depth interval, amount of organic matter starts to predominate (20%–65%). Accumulation of moss fen peat (<i>Bryalo-Parvocaricioni bryaleti</i> composed of <i>Bryales</i> pl. sp. <i>Carex</i> sp. and <i>Menyanthes trifoliata</i>) is initiated with only some admixture of minerogenic matter.
KT-L5 345–300 cm	The lower part of this zone shows LOI values at first decreasing from ca. 65% to ca. 30% in a result of minerogenic matter admixture to the woody alder peat (<i>Alnioni aneti</i> composed of <i>Bryales</i> pl. sp. and decomposed <i>Alnus</i> sp. wood). In the upper part, LOI curve starts rising again reaching values slightly over 85% as a result of almost pure uncontaminated moss fen peat accumulation (<i>Bryalo-Parvocaricioni bryaleti</i> composed mostly of <i>Bryales</i> pl. sp. and wood).
KT-L6 300–255 cm	At the beginning of this zone LOI values remain high (up to ca. 65–80%) due to continued accumulation of moss fen peat (<i>Bryalo-Parvocaricioni bryaleti</i> composed mostly of <i>Bryales</i> pl. sp. and – depending on depth – by <i>Drepanocladus</i> sp., <i>Aulacomnium palustre</i> , <i>Bryum</i> sp., <i>Carex gracilis</i> , <i>Carex lasiocarpa</i> and <i>Menyanthes trifoliata</i>). With decreasing depth, distinct periods with enhanced mineral delivery interrupt peat accumulation – near the upper boundary LOI curve drops below 40%.
KT-L7 255–225 cm	LOI values fluctuates between ca. 25–35%, resulting from a large admixture of mineral sediment to organic deposits. In the upper part of this zone, LOI curve slightly rises again due to sedge peat accumulation (<i>Magnocaricioni cariceti</i>

	composed of <i>Carex gracilis</i> , <i>Carex fusca</i> , <i>Carex hudsoni</i> , <i>Carex</i> sp., <i>Menyanthes trifoliata</i> , <i>Phragmites australis</i> , <i>Equisetum limosum</i> , <i>Bryales</i> sp.).
KT-L8 225–185 cm	In this interval LOI curve increases gradually with some minor fluctuations from ca. 30 to 65%, as a result of decreasing input of minerogenic matter and accumulation of moss fen peat (<i>Bryalo-Parvocaricioni bryaleti</i> composed mostly of <i>Bryales</i> sp., <i>Carex gracilis</i> , <i>Carex</i> sp. and <i>Menyanthes trifoliata</i>) and later also woody alder peat (<i>Alnioni aneti</i> composed of <i>Alnus glutinosa</i> , <i>Bryales</i> sp., and subsequently by <i>Carex gracilis</i> and <i>Carex</i> sp.).
KT-L9 185–155 cm	In this subzone, moss fen peat accumulation (<i>Bryalo-Parvocaricioni bryaleti</i> composed mostly of <i>Bryales</i> sp., <i>Scorpidium scorpioides</i> , <i>Carex gracilis</i> , <i>Carex</i> sp. and <i>Sphagnum teres</i>) reaches again its maximum (up to 70% on the LOI curve), however, above the depth of ca. 170 cm it starts to decrease (at first to ca. 50%.) due to delivery of minerogenic matter.
KT-L10 155–125 cm	In this depth interval decreased LOI values remain fluctuating around ca. 35–45%, reflecting the increased minerogenic matter input into the sedge-moss fen peat (<i>Bryalo-Parvocaricioni cariceto-bryaleti</i> composed mostly of <i>Carex</i> pl. sp. and <i>Bryales</i> sp.).
KT-L11 125–117.5 cm	In this thin interval LOI values show one of the most abrupt decreases, slightly below ca. 20%, of the entire profile due to greatly enhanced minerogenic matter delivery.
KT-L12 117.5–90 cm	In this subzone LOI values rises slightly close to 30% due to organic matter accumulation – sedge-moss fen peat <i>Bryalo-Parvocaricioni cariceto-bryaleti</i> composed mostly of <i>Carex</i> sp., <i>Carex gracilis</i> sp., <i>Bryales</i> sp. and wood (<i>Salix</i> ?). Close to the upper boundary sedimentation of minerogenic cover begins (LOI values decrease again).
KT-L13 90–65 cm	In this zone minerogenic cover (clay) is deposited, therefore LOI values drop to very low, oscillating around 15%.
KT-L14 65–25 cm	LOI values start to gradually increase throughout this zone, reaching level around 30%, as organic matter content is increasing (humified peat, strongly decomposed, consisting of <i>Carex gracilis</i> , <i>Carex</i> sp., wood and other unidentified components).
KT-L15 25–0 cm	In the most recent layer, accumulation of sedge peat (<i>Magnocaricioni cariceti</i> consisting of <i>Carex gracilis</i> , <i>Carex rostrata</i> and <i>Carex</i> sp.) takes place, what is shown on LOI curve as a further rise to ca. 55%.

200 **Macrofossil data**

201 **Figure S3.** CONISS dendrogram and delineated LMAZ and palaeoecological stages of
202 development for the macrofossil data of the Klaklowo landslide fen deposits.

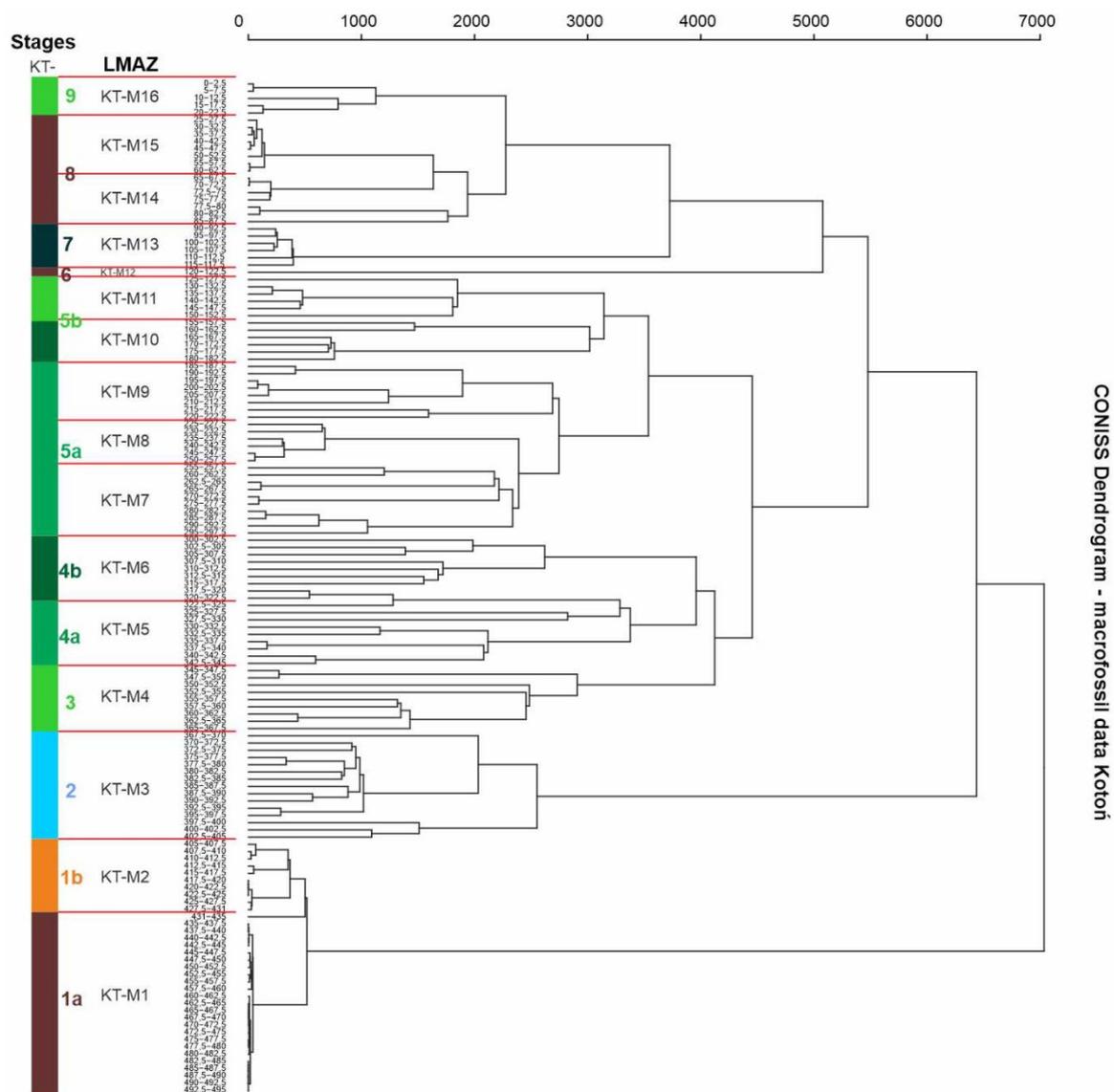


203

204

205

206 **Figure S4.** CONISS dendrogram and delineated LMAZ and palaeoecological stages of
207 development for the macrofossil data of the Kotoń landslide fen deposits.



208

209

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46

210 Table S5. Results of macrofossil analysis of the Klaklowo landslide fen deposits divided into local macrofossil assemblage zones (LMAZ) and
211 palaeoecological stages of the landslide fen development (see Klaklowo fen macrofossil diagram in Figure 4).

LMAZ	Results of plant macrofossil analysis
Stage KK-1 (367–330 cm, > from ca. 14,630 ± 349 to ca. 14,040 ± 61 cal BP, ca. >590 years) Landslide formation and waterbody I/ steppe-tundra	
KK-M1 (367.0–357.5 cm)	Detail description of LMAZ can be found in Pilch et al. (2025b).
KK-M2 (357.5–350.0 cm)	
KK-M3 (350.0–347.5 cm)	
KK-M4 (347.5 –330.0 cm)	
Stage KK-2 (330.0–307.5 cm, from ca. 14,040 ± 61 to ca. 13,870 ± 54 cal BP, ca. 170 years) Short-lasting fen/ steppe-tundra	
KK-M5 (330.0–322.5 cm)	Detail description of LMAZ can be found in Pilch et al. (2025b).
KK-M6 (322.5 –315.0 cm)	
KK-M7	

(315.0–307.5 cm)	
Stage KK-3a (307.5–295.0 cm, from ca. 13,870 ± 54 to ca. 13,790 ± 57 cal BP, ca. 80 years) Colonization of waterbody II/ <i>Betula</i> -dominated boreal forest	
KK-M8 (307.5–295.0 cm)	Detail description of LMAZ can be found in Pilch et al. (2025b).
Stage KK-3b (295.0–267.5 cm, from ca. 13,790 ± 57 to ca. 13,620 ± 39 cal BP, ca. 170 years) Waterbody II overgrowing/ <i>Betula</i> -dominated boreal forest	
KK-M9 (295.0–267.5 cm)	Detail description of LMAZ can be found in Pilch et al. (2025b).
Stage KK-4 (267.5–217.5 m, from ca. 13,620 ± 39 to ca. 13,200 ± 82 cal BP, ca.420 years) Long-lasting fen - wetter conditions and moss fen peat accumulation / <i>Pinus-Larix-Betula</i> boreal forest	
KK-M10 (267.5–232.5 cm)	<p>Trees, shrubs and dwarf shrubs are represented by a continuous presence and a high number of <i>Pinus sylvestris</i> macrofossils; only at a depth of 245-247.5 cm their number suddenly drops and later increases again. Fragments of male cones of <i>Pinus sylvestris</i> are also present at some depths. An increasing number of needles of <i>Larix decidua</i> along with a continuous presence and a high number of Coniferae bud scales can be noticed.</p> <p>There is a decreasing number of so-far abundant fruit and fruit scales of <i>Betula nana</i>, until a sample 245–247.5 cm when it totally drops to 0; later it reappears in smaller numbers. At some depths, the presence of <i>Betula</i> sect. <i>Nanae</i> and <i>Betula humilis</i> can be noticed. Macrofossils of <i>Betula pubescens</i> show continuous presence, fluctuating and slightly declining upward. <i>Betula</i> sect. <i>Albae</i> and <i>Betula</i> sp. appear at some depths. Moreover, several bud scales of <i>Populus tremula</i> appears in in one sample at a depth of 241.5 cm. Fragments of leaves (undiff.) are abundant.</p> <p>Plants of fresh and moist habitats are represented by small but continuous share of Poaceae fruits, along with some appearance of <i>Poa</i> cf. <i>pratensis</i> fruits. There are also single occurrences of <i>Taraxacum</i> sp. and <i>Cirsium oleraceum</i>. <i>Urtica dioica</i> fruits appear in some samples.</p> <p>Among mire plants, <i>Carex rostrata</i> and <i>Carex diandra</i> show continuous occurrence, decreasing from the highest values (of the entire Klaklowo profile) recorded in the bottom part to the smaller values toward the upper boundary (minimum around</p>

	<p>247.5 cm). Bryopsida show a similar trend to sedges, decreasing from the highest values recorded in the bottom parts to smaller but continuous share in the upper part.</p> <p>Moreover, there are single occurrences of macrofossils of <i>Scirpus sylvaticus</i>, <i>Eleocharis palustris</i>, <i>Caltha palustris</i> at various depth of this interval. <i>Thelypteris palustris</i> appear in some samples. <i>Glyceria</i> cf. <i>maxima</i> is also present.</p> <p>Aquatic plants are represented by continued abundant oospores of Characeae which quickly disappear within the lower part of this interval. They again reappear in a depth interval of 245–250 cm but later decline again. In the bottommost samples, <i>Hippuris vulgaris</i> continues its presence from the previous zone.</p> <p>Among the animal remains, Ostracoda shells appear in small amounts throughout this zone, similarly, to single occurrences of macroremains of <i>Daphnia</i> sp., Porifera and <i>Plumatella</i> sp. Trace occurrences of Chironomidae and Trichoptera can be observed. Oribatid mites are still abundant.</p>
<p>KK-M11 (232.5–217.5 cm)</p>	<p>Trees, shrubs and dwarf shrubs are represented by abundant macrofossils of <i>Pinus sylvestris</i> and <i>Larix decidua</i> (the highest values of the entire profile). Coniferae bud scales are also present. Fruits and fruit scales of <i>Betula nana</i> almost disappear in this interval, whereas <i>Betula pubescens</i> decrease in number. One seed of <i>Sorbus aucuparia</i> was found in this interval.</p> <p>Plants of fresh and moist habitats are represented by some fruits of Poaceae. A few fruits of <i>Lapsana communis</i> are present and there is also some occurrence of <i>Urtica dioica</i>.</p> <p>Mire habitats are represented by a significant share of macrofossils of <i>Carex rostrata</i> and <i>Carex diandra</i>. Moreover, single occurrences of <i>Carex dioica</i> cf. and <i>Carex</i> cf. <i>pseudocyperus</i> were registered. Other numerous macrofossils belong to <i>Caltha palustris</i> and <i>Filipendula ulmaria</i>. Bryopsida are also present in a noticeable amount. There are also some occurrences of <i>Valeriana simplicifolia/dioica</i> and <i>Thelypteris palustris</i>. Reedswamp plant taxa are represented by a few fruits of <i>Phragmites australis</i> and <i>Glyceria</i> cf. <i>maxima</i>.</p> <p>Among macrofossils of aquatic plants, some occurrences of Characeae and <i>Hippuris vulgaris</i> were recorded.</p> <p>Other minor groups of macrofossils include: sclerotia of <i>Cenococcum geophilum</i> and Oribatid mites. Noticeable is the lack of Ostracoda shells.</p>
<p>Stage KK-5a (217.5–167.5 cm, from ca. 13,200 ± 82 to ca. 12,320 ± 122 cal BP, ca. 880 years)</p> <p>Long-lasting fen – less wet conditions and more minerogenic delivery/ <i>Pinus-Larix-Betula</i> boreal forest</p>	
<p>KK-M12 (217.5–167.5 cm)</p>	<p>Minerogenic horizon at 217.5–207.5 cm depth:</p> <p>In term of trees, shrubs and dwarf shrubs, a minerogenic horizon corresponds to a decreased share of needle fragments of <i>Pinus sylvestris</i> and Coniferae bud scales, however, <i>Larix decidua</i> macrofossils are present abundantly. Fruits and fruit scales</p>

	<p>of <i>Betula nana</i> are almost absent, whereas of <i>Betula pubescens</i> and <i>Betula</i> sect. <i>Albae</i> occur in a small number. Several bud scales of <i>Populus tremula</i> appear in this interval.</p> <p>Among other plant taxa there is a single occurrence of <i>Carex rostrata</i>, some Bryopsida stems and <i>Filipendula ulmaria</i> fruits. Among animal remains, Ostracoda, Oribatid mites and Trichoptera larval cases are present.</p> <p>The remaining part of the zone:</p> <p>Trees, shrubs and dwarf shrubs are represented by needles fragments of <i>Pinus sylvestris</i> which tend to increase in number up to the middle part of the zone and later decrease gradually. Fragments of needles of <i>Larix decidua</i> are also abundant. Coniferae bud scales are continuously present in a noticeable number. Macrofossils of <i>Betula nana</i> and <i>Betula pubescens</i> occur in significant quantities, secondarily also <i>Betula</i> Sect. <i>Albae</i> and <i>Betula</i> sp macrofossils. Leaf fragments (undiff.) are abundant.</p> <p>Plants of fresh and moist habitats are represented by a few fruits of Poaceae and <i>Poa</i> cf. <i>pratensis</i>. Single occurrence of <i>Alchemilla</i> sp. fruit was recorded.</p> <p>Mire plants: there is a noteworthy almost total lack of <i>Carex rostrata</i> macrofossils along with the other taxa of sedges and continued presence of <i>Caltha palustris</i> seeds and <i>Filipendula ulmaria</i> fruits. Bryopsida are continuously present throughout the zone, mostly in a small amount and in increased amount near the upper boundary of the zone. Single appearances of <i>Thelypteris palustris</i> is also noticed.</p> <p>Animal remains are represented by a small but continuous number of Ostracoda and numerous Oribatid mites and Trichoptera larval cases.</p>
<p style="text-align: center;">Stage KK-5b (167.5–127.5 cm, from ca. 12,320 ± 122 to ca. 11,240 ± 92 cal BP, ca. 1080 years)</p> <p style="text-align: center;">Long lasting fen – Wetter conditions (moss fen peat accumulation) and later less drier conditions (total disappearance of Bryopsida)/<i>Larix-Pinus-Betula</i> boreal forest</p>	
<p>KK-M13 (167.5–145 cm)</p>	<p>Among trees, shrubs and dwarf shrubs, there is a decreasing number of needle fragments of <i>Pinus sylvestris</i>, numerous needle fragments of <i>Pinus</i> sp. in one sample; abundant needles of <i>Larix decidua</i>, Coniferae bud scales present in small amounts. Moreover, there are single occurrences of macrofossils of <i>Betula pubescens</i> and <i>Betula nana</i>. Numerous undifferentiated leaf fragments appear.</p> <p>Plants of fresh and moist habitats are represented by several fruits of <i>Poa</i> cf. <i>pratensis</i>, as well as a single fruit of <i>Rumex</i> cf. <i>scutatus</i>.</p>

	<p>Mire plants are represented by numerous macroremains of Bryopsida and, to a lesser degree, by <i>Carex rostrata</i>. In the Others group, animal remains, Oribatid mites and Trichoptera larval cases are abundant. Chironomidae are present along with a few Ostracoda shells.</p>
<p>KK-M14 (145–127.5 cm)</p>	<p>Trees, shrubs and dwarf shrubs are represented by a continuing low number of needles of <i>Pinus sylvestris</i> and Coniferae bud scales and needles of <i>Larix decidua</i> present abundantly. There is a noticeable presence of <i>Betula pubescens</i> fruits, single occurrence of <i>Betula nana</i> fruit and several leaf fragments of <i>Salix</i> sp. determined in the uppermost sample. Moreover, other undeterminable leaf fragments (also of <i>Salix</i> sp.?) are abundant in this interval.</p> <p>Plants of fresh and moist habitat are represented by several fruits of Poaceae and <i>Poa</i> cf. <i>pratensis</i>.</p> <p>Mire plants group is characterized by a single occurrence of <i>Valeriana simplicifolia/dioica</i>, macrofossils of <i>Carex rostrata</i> and Bryopsida stems number diminished to trace amounts, numerous fruits of <i>Carex diandra</i> in the lowermost sample. There is a single occurrence of <i>Thelypteris palustris</i>.</p> <p>Aquatic habitat is marked by a single macrofossil of <i>Batrachium</i> sp. and several Ostracoda shells. Animal remains and Oribatid mites are common and there is a noticeable presence of Trichoptera (larval cases).</p>
<p>Stage KK-6 (127.5–80 cm, from ca. 11,240 ± 92 to ca. 11,120 ± 99 cal BP, ca. 120 years) <i>Sedge peat, minerogenic layer and woody birch peat accumulation – at a rate of ca. 4.20 mm year⁻¹/ open space, Pinus-Betula-Larix tree stands</i></p>	
<p>KK-M15 (127.5–92.5 cm)</p>	<p>Trees, shrubs and dwarf shrubs are characterized by almost total disappearance of macrofossils of <i>Pinus sylvestris</i> and reduction of the number of <i>Larix decidua</i> needles Coniferae bud scales to rare occurrences. Macrofossils of <i>Betula nana</i>, <i>Betula</i> sect. <i>Nanae</i>, <i>Betula</i> sect. <i>Albae</i> and <i>Betula</i> sp. are present in small amounts in some samples of this interval, whereas macrofossils of <i>Betula pubescens</i> are recorded continuously, mostly also in small quantities. Leaf scars are continuously present throughout this zone.</p> <p>Plants of fresh and moist habitats: in the lower part of this interval a small amount of Poaceae fruits is registered.</p> <p>Among mire plants, in the lower part of this interval a noticeable share of <i>Carex nigra</i> fruits is visible. Moreover, in the lowermost sample there are single occurrences of <i>Caltha palustris</i> and <i>Filipendula ulmaria</i>, whereas in the upper part there is a single appearance of <i>Scirpus sylvaticus</i>. In the middle part there is a lack of mire plants representatives, whereas in the uppermost sample fruit and urticles of <i>Carex canescens</i> appear for the first time.</p>

	Among Others group, in the upper part of the zone there are numerous sclerotia of <i>Cenococcum geophilum</i> . Beside a noticeable amount of Oribatid mites, there are single occurrences of Ostracoda and Chironomidae. Animal remains are numerous.
KK-M16 (92.5–80 cm)	Among trees, shrubs and dwarf shrubs there are abundant needle fragments of <i>Pinus sylvestris</i> , whereas that of <i>Larix decidua</i> are present in small amounts. In the lower part of this zone, there is also a single bud scale of <i>Abies alba</i> ; some Coniferae bud scales, a few fruits of <i>Betula nana</i> and more abundant macrofossils of <i>Betula pubescens</i> ; a single bud scale of <i>Populus tremula</i> and a noticeable number of leaf scars. Mire plants are represented by a single occurrence of <i>Valeriana simplicifolia/dioica</i> , <i>Thelypteris palustris</i> and <i>Phragmites australis</i> ; more abundant fruits of <i>Filipendula ulmaria</i> , numerous macrofossils of <i>Carex canescens</i> , and less abundant of <i>Carex nigra</i> and <i>Carex</i> sp. trigonus. Animal remains are represented by some amount of Oribatid mites.
Stage KK-7 (80–22.5 cm, from ca. 11,120 ± 99 cal BP - beyond age-depth model) Accumulation of minerogenic cover (waterbody) on woody birch peat	
KK-M17 (80–22.5 cm)	This interval is characterized by a large number of macrofossils of <i>Scirpus sylvaticus</i> (redeposited?) and sclerotia of <i>Cenococcum geophilum</i> . There is a noticeable presence of <i>Sambucus racemosa</i> and <i>Rubus idaeus</i> and trace amount of <i>Betula pubescens</i> and <i>Betula</i> sp. in the lower part of the zone. Plants of fresh and moist habitats are represented by single occurrence of the <i>Ajuga reptans</i> fruit and <i>Juncus</i> seed. Animal remains are present in the lower part of the zone, but later almost their complete disappearance can be noticed.
Stage KK-8 (22.5–0 cm, beyond age-depth model) Present-day sedge fen	
KK-M18 (22.5–0 cm)	This zone is dominated by macrofossils of <i>Juncus</i> sp., <i>Carex canescens</i> and <i>Carex paniculata</i> , with a secondary occurrence (a few individuals) of <i>Cirsium palustre</i> , <i>Lychnis flos-cuculi</i> , <i>Lycopus europaeus</i> . <i>Scirpus sylvaticus</i> fruits reappear in large number in the topmost samples (what is in agreement with a present-day occurrence in the fen). Sclerotia of <i>Cenococcum geophilum</i> are continuously present from the previous interval only in a lower part. Animal remains show increased number comparing to underlying interval, sporadically also Porifera and Chironomidae occur.

213 **Table S6.** Results of macrofossil analysis of the Kotoń landslide fen deposits divided into local macrofossil assemblage zones (LMAZ) and
 214 palaeoecological stages of the landslide fen development (see Kotoń fen macrofossil diagram in Figure 5).

LMAZ	Results of plant macrofossil analysis
Stage KT-1 (500–405 cm, from > ca. 14,240, ± 103 to ca. 14,070 ± 72 cal BP) Waterbody/ open space	
KT-1a/ KT-M1 (500–431 cm)	Detail description of LMAZ can be found in Pilch et al. (2025a).
KT-1b/ KT-M2 (431–405 cm)	
Stage KT-2 (405–367.5 cm, from ca. 14,070 ± 72 to ca. 13,900 ± 56 cal BP, ca. 170 years) Waterbody – aquatic succession/ steppe-tundra	
KT-M3 (405–367.5 cm)	Detail description of LMAZ can be found in Pilch et al. (2025a).
Stage KT-3 (367.5–345 cm, from ca. 13,900 ± 56 to ca. 13,820 ± 68 cal BP, ca. 80 years) Calcareous extremely rich fen /steppe-tundra	
KT-M4 (367.5–345 cm)	Detail description of LMAZ can be found in Pilch et al. (2025a).
Stage KT-4a and b (345–300 cm, from ca. 13,820 ± 68 to ca. 13,500 ± 115, ca. 320 years) Moderately rich fen/ <i>Betula</i> boreal forest	
KT-4a/KT-M5 (345–322.5 cm)	Detail description of LMAZ can be found in Pilch et al. (2025a).

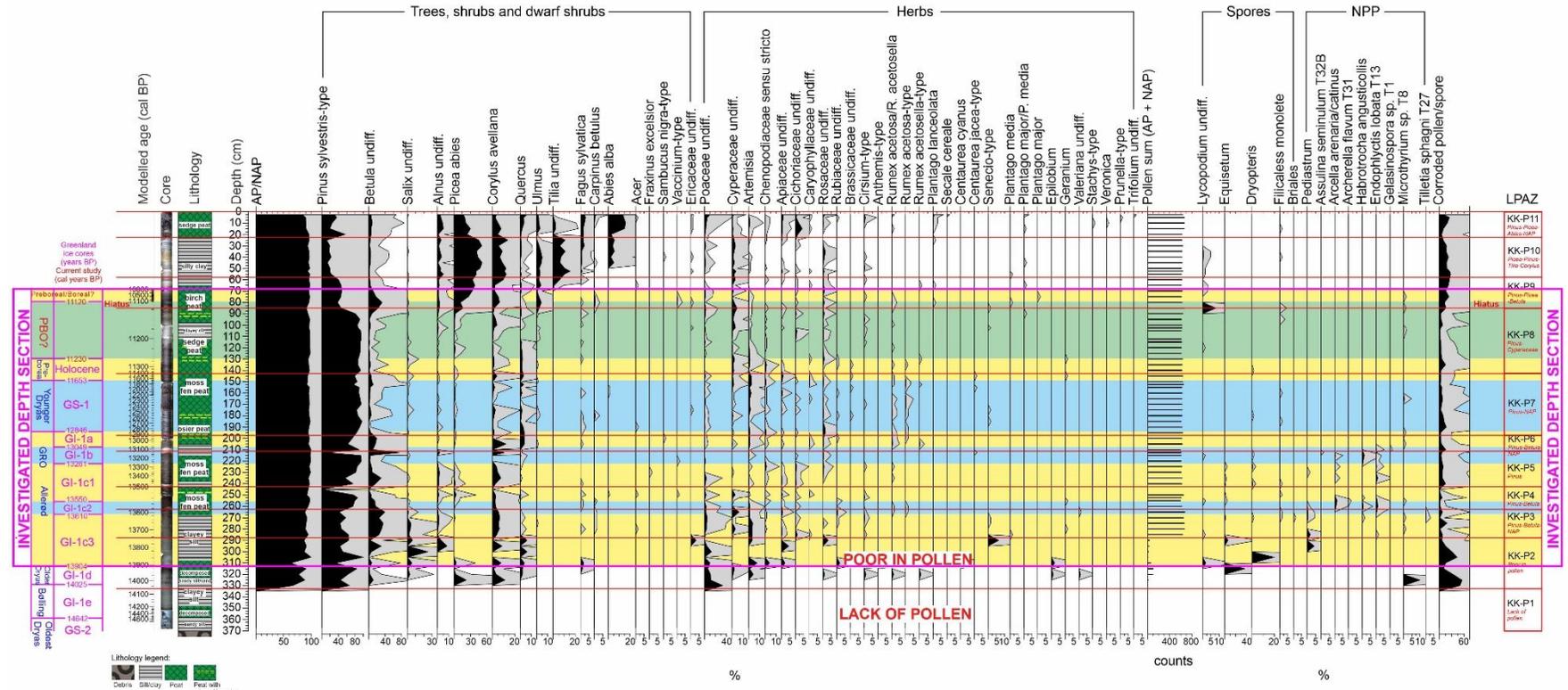
KT-4b/KT-M6 (322.5–300 cm)	
<p style="text-align: center;">Stage KT-5a (300–185 cm, from ca. 13,500 ± 115 to ca. 11,890 ± 104 cal BP, ca. 1610 years) Long-lasting fen – less wet conditions and more minerogenic delivery/ <i>Betula-Pinus</i> boreal forest</p>	
KT-M7 (300–255 cm)	<p>Trees, shrubs and dwarf shrubs are represented by several needle fragments of <i>Pinus sylvestris</i> (which appear more frequently in the upper part of this zone), several bud scales of Coniferae and one <i>Picea abies</i> seed. Macrofossils of <i>Betula pubescens</i> occur continuously. There is a single occurrence of leaves fragments of <i>Salix</i> sp. Leaf fragments (undiff.) are frequent in this zone.</p> <p>Mire plants are represented by high amount of Bryopsida stems and numerous macrofossils of <i>Carex nigra</i> and <i>Carex diandra</i>, there is also some small share of <i>Carex rostrata</i> (which increases greatly only in the uppermost sample). There are also frequent seeds of <i>Stellaria palustris</i>, less numerous seeds of <i>Menyanthes trifoliata</i> and sporadic macrofossils of <i>Scirpus sylvaticus</i>, <i>Caltha palustris</i> and <i>Thelypteris palustris</i>.</p> <p>In the group of Others, a single Ostracoda shell was found. Larval cases of Trichoptera and Oribatid mites are more abundant.</p>
KT-M8 (255–225 cm)	<p>Among trees, shrubs and dwarf shrubs, there is a significant occurrence of <i>Pinus sylvestris</i> needles fragments, Coniferae bud scales, some fruits of <i>Betula nana</i> and continuous presence of <i>Betula pubescens</i>. Leaves fragments appear in a high amount. In this interval, there is also a single fruit of Poaceae.</p> <p>Mire plants are again represented by fluctuating abundance of macrofossils of <i>Carex diandra</i>, <i>Carex rostrata</i> and <i>Carex nigra</i>. Bryopsida stems are reduced in number and less frequent. Sporadically, seeds of <i>Caltha palustris</i> and <i>Stellaria palustris</i> can be found. In the group of Others, almost the same taxa as in the previous zone occur.</p>
KT-M9 (225–185 cm)	<p>Trees, shrubs and dwarf shrubs are represented by continuing occurrence of <i>Pinus sylvestris</i> needles fragments, Coniferae bud scales and macrofossils of <i>Betula pubescens</i>. Moreover, there are a few fragments of <i>Larix decidua</i> needles found in several samples, as well as single fruits of <i>Betula nana</i>, <i>Betula</i> sect. <i>Albae</i> and <i>Rubus</i> cf. <i>sulcatus</i>. In the lower part of this zone, leaves fragments occur abundantly, along with numerous leaves of <i>Salix</i> sp. identified in one of the samples.</p> <p>Among plants of fresh and moist habitats, there is a single fruit of <i>Potentilla</i> cf. <i>crantzii</i>. Mire plants are dominated by fruits and urticles of <i>Carex canescens</i> and high quantity of Bryopsida stems fragments (however present discontinuously). <i>Carex rostrata</i>, <i>Carex diandra</i>, <i>Stellaria palustris</i>, <i>Scirpus sylvaticus</i> and <i>Menyanthes trifoliata</i> occur sporadically. Among animal</p>

	remains, there are single appearances of Ostracoda shells. Oribatid mites and Trichoptera larval cases can be found frequently in a noticeable amount.
<p>Stage KT-5b (185–125 cm, from ca. 11,890 ± 104 cal BP to ca. 11,260 ± 263, ca. 630 years)</p> <p>Long lasting fen – Wetter conditions (moss fen peat accumulation) and later drier conditions (total disappearance of Bryopsida)/ <i>Pinus-Larix</i> boreal forest, later open space with tree stands</p>	
KT-M10 (185–155 cm)	Macrofossils of trees, shrubs and dwarf shrubs are dominated by needle fragments of <i>Larix decidua</i> . Moreover, this group is represented by a few needle fragments of <i>Pinus sylvestris</i> , single seed of <i>Picea abies</i> , single fruit of <i>Juniperus communis</i> , single bud scales of Coniferae and small amount of <i>Betula pubescens</i> fruits. Noticeably, fragments of leaves completely disappear in this interval. Among plants of fresh and moist habitats single fruits of <i>Potentilla</i> cf. <i>crantzii</i> and <i>Taraxacum</i> sp. were identified. Macrofossils of mire plants are dominated by continuously occurring abundant fruits of <i>Carex rostrata</i> and a high amount of Bryopsida stems. Less numerous but also continuous is the occurrence of <i>Carex canescens</i> fruits and fruit scales. <i>Carex nigra</i> and <i>Carex diandra</i> appear sporadically. Moreover, there are single appearances of <i>Valeriana simplicifolia/dioica</i> and <i>Filipendula ulmaria</i> . Animal remains are represented by a few ehippia of <i>Daphnia</i> sp. and abundant Oribatid mites.
KT-M11 (155–125 cm)	In this interval, <i>Pinus sylvestris</i> needles and Coniferae bud scales disappear, whereas scarce needles of <i>Larix decidua</i> occur only in the bottommost samples and later also cease completely. Except for the uppermost sample of this zone, the number of macrofossils of <i>Betula pubescens</i> is also marginal. There is a single occurrence of <i>Rubus</i> cf. <i>sulcatus</i> and some fragments of leaves. Mire plants are represented by macrofossils of <i>Carex canescens</i> , whereas <i>Carex rostrata</i> is reduced in number and reappears in the uppermost samples, along with fruits of <i>Scirpus sylvaticus</i> . Bryopsida disappears in this zone and shows no return throughout later stages. There is a single fruit of <i>Filipendula ulmaria</i> found. Animal remains are represented by single shells of Ostracoda and a few Oribatid mites.
<p>Stage KT-6 (125–117.5 cm, from ca. 11, 260 ± 263 to ca. 10,990 ± 432 cal BP, ca. 270 years)</p> <p>Minerogenic material delivery</p>	
KT-M12 (125–117.5 cm)	In this interval single macrofossils of <i>Betula</i> sect. <i>Nanae</i> and <i>Betula pubescens</i> were found. Mire plants are represented by numerous fruits and urticles of <i>Carex rostrata</i> and very abundant fruits of <i>Scirpus sylvaticus</i> . There is a single finding of <i>Filipendula ulmaria</i> fruit.
<p>Stage KT-7 (117.5–87.5 cm, from ca. 10,990 ± 432 to ca. 8380 ± 591 cal BP, ca. 2610 years)</p> <p>Fen with <i>Scirpus sylvaticus</i> (drier conditions) and minerogenic material delivery</p>	

KT-M13 (117.5–87.5 cm)	Macrofossils of trees, shrubs and dwarf shrubs are represented by fragments of needles of <i>Picea abies</i> , fruits of <i>Sambucus racemosa</i> and <i>Rubus idaeus</i> . Plants of fresh and moist habitats are represented by fruits of <i>Ajuga reptans</i> and seeds of <i>Juncus</i> sp. Mire plants are represented by abundant fruits of <i>Scirpus sylvaticus</i> . There is some sclerotia of <i>Cenococcum geophilum</i> .
Stage KT-8 (87.5–22.5 cm, from ca. 8380 ± 591 cal BP - beyond age-depth model) Accumulation of minerogenic cover (waterbody)	
KT-M14 (87.5–65 cm)	The most visible feature of this interval is the abundant occurrence of <i>Cenococcum geophilum</i> sclerotia. Macrofossils of trees, shrubs and dwarf shrubs are continuously represented by a noticeable number of fruits of <i>Sambucus racemosa</i> and <i>Rubus idaeus</i> . <i>Scirpus sylvaticus</i> fruits are reduced in number.
65 cm – HIATUS	
KT-M15 (65–22.5 cm)	In this interval trees, shrubs and dwarf shrubs are represented by numerous fragments of needles of <i>Abies alba</i> (also single fragment of <i>Picea abies</i>) and a noticeable number of fruits of <i>Sambucus racemosa</i> and <i>Rubus idaeus</i> . Among plants of fresh and moist habitats macrofossils of <i>Ajuga reptans</i> , <i>Juncus</i> sp. and <i>Potentilla</i> cf. <i>alba</i> occur. Mire plants are represented by sporadic occurrence of <i>Carex</i> cf. <i>flava</i> and <i>Carex canescens</i> . Sclerotia of <i>Cenococcum geophilum</i> cease in number.
Stage KT-9 (25–0 cm, beyond age-depth model) Present day sedge fen	
KT-M16 (22.5–0 cm)	Trees, shrubs and dwarf shrubs are represented only by one sample with numerous fragments of needles of <i>Abies alba</i> . Again, there are a few findings of <i>Ajuga reptans</i> , <i>Juncus</i> sp. and <i>Potentilla</i> cf. <i>alba</i> . Mire plants are continuously represented by macrofossils of <i>Carex</i> cf. <i>flava</i> and <i>Carex canescens</i> , which in this interval become abundant. There are also single larval cases of Trichoptera.

217 **Pollen and NPPs data**

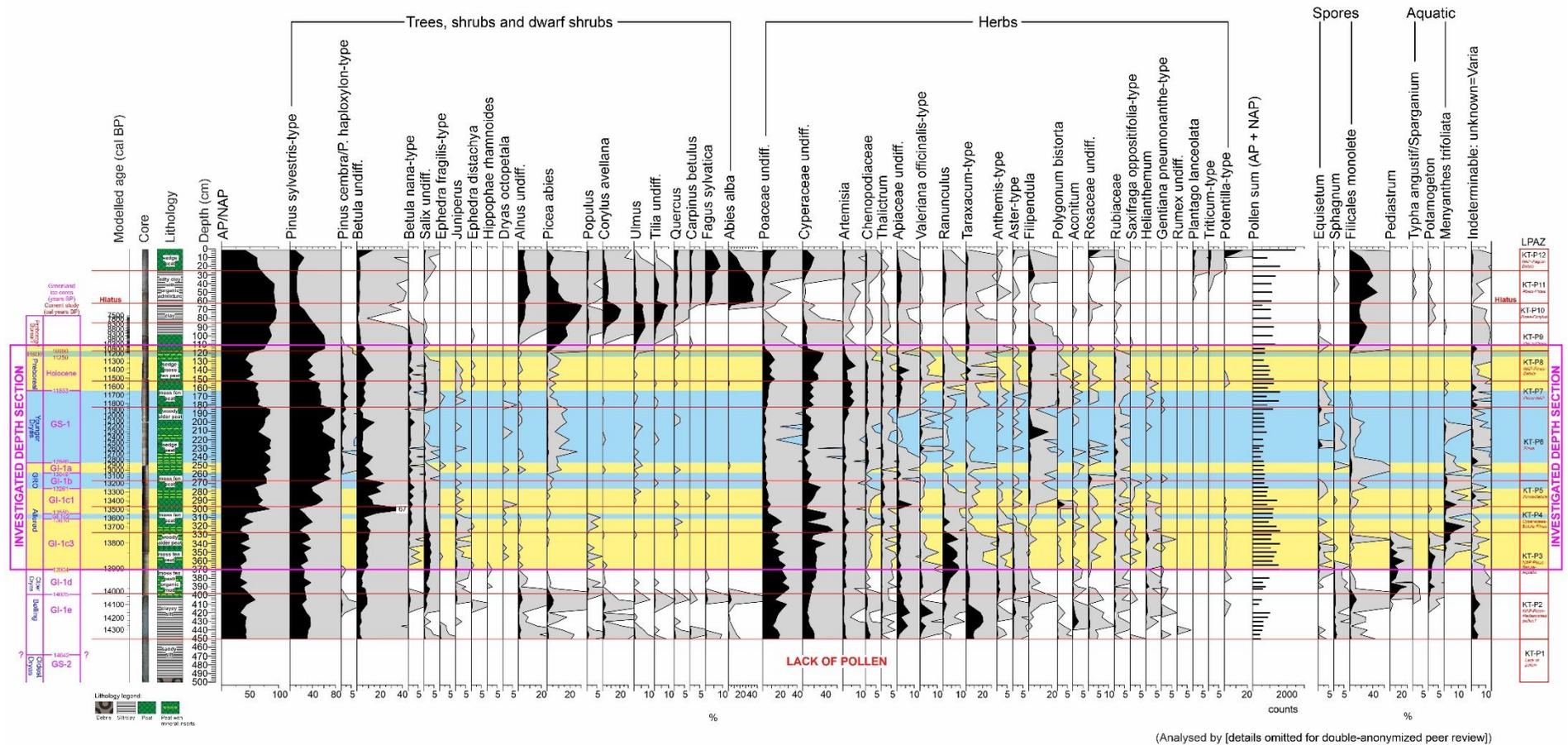
218 **Figure S5.** Pollen-percentage diagram of the Klaklowo landslide fen deposits divided into LPAZ and compared with Greenland ice cores event
219 stratigraphy and corresponding traditional stratigraphic division (in blue), GRO – Gerzensee oscillation, Al. – Allerød, PBO – the supposed
220 Preboreal oscillation. In the background: climatic oscillations according to the Greenland ice cores event stratigraphy (Rasmussen et al., 2014)
221 (pale yellow – warming, pale blue – cooling, pale green – presumably cooling). See SM Table S7 for detailed description of the LPAZ. Notice
222 that for convenience pollen data from the zone KK-P2 is expressed as percentage data, but it is not interpretable due to pollen scarcity.
223 Investigated depth section (pink rectangle) – depth/time interval analysed in the current paper.



(Analysed by [details omitted for double-anonymized peer review])

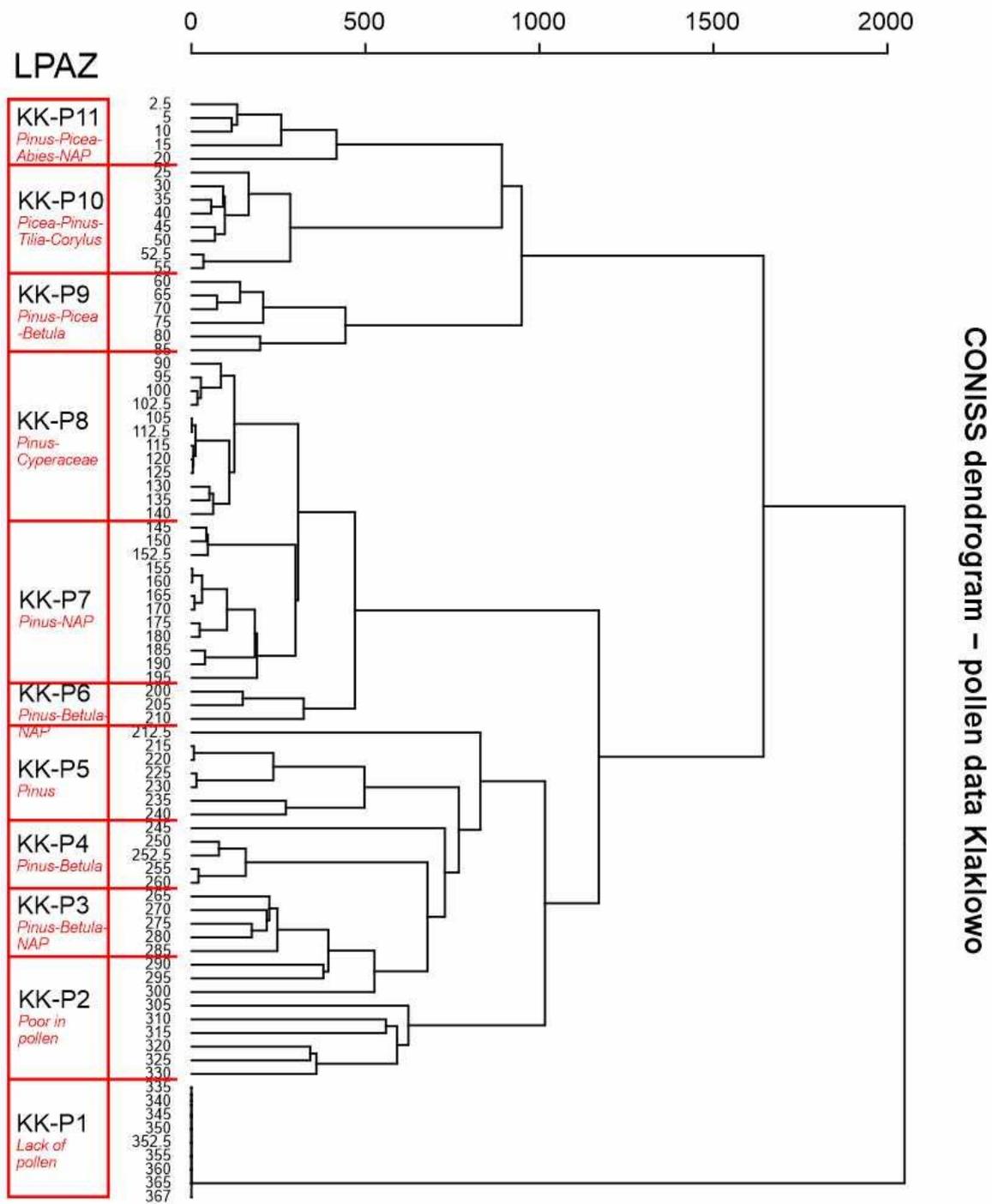
224

225 **Figure S6.** Pollen-percentage diagram based on the results of the earlier pollen analysis of the Kotoń landslide fen deposits (Margielewski,
 226 2001b; Margielewski et al., 2003) divided into LPAZ and compared with Greenland ice cores event stratigraphy and corresponding traditional
 227 stratigraphic division (in blue), GRO – Gerzensee oscillation, Al. – Allerød, PBO – the supposed Preboreal oscillation. In the background:
 228 climatic oscillations according to the Greenland ice cores event stratigraphy (Rasmussen et al., 2014) (pale yellow – warming, pale blue –
 229 cooling, pale green – presumably cooling). See SM Table S8 for detailed description of the LPAZ. Investigated depth section (pink rectangle) –
 230 depth/time interval analysed in the current paper.



231

232 **Figure S7.** CONISS dendrogram and delineated LPAZ for the pollen data of the Klaklwo
233 landslide fen deposits.

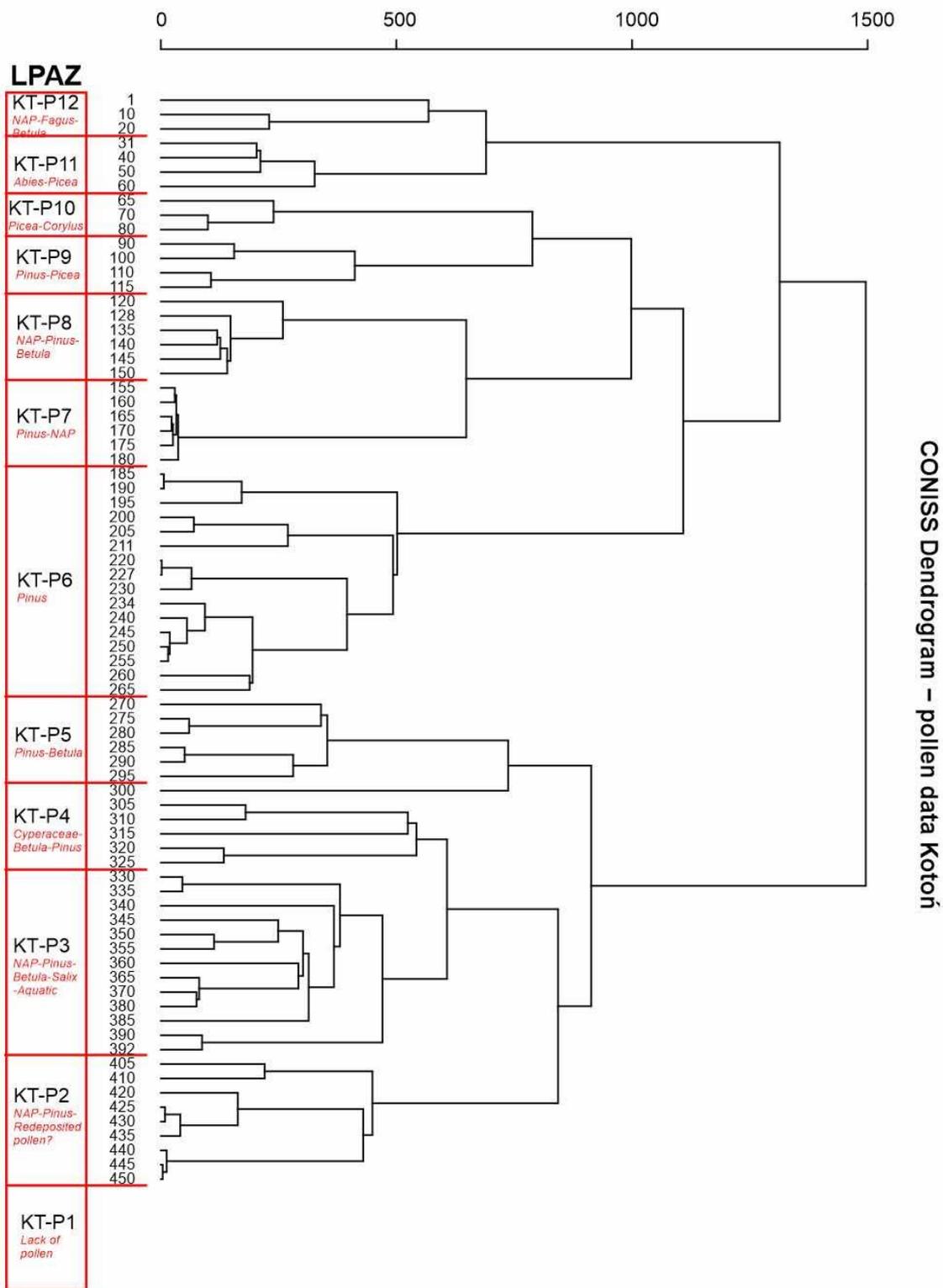


234

235

236

237 **Figure S8.** CONISS dendrogram and delineated LPAZ for the pollen data of the Kotoń
 238 landslide fen deposits.



239

240 **Table S7.** Results of pollen analysis of the Klaklowo landslide fen deposits divided into LPAZ (see pollen diagram in SM Figure S5).

LPAZ	Results of pollen analysis
KK-P1 (367–332.5 cm) Lack of pollen	The entire pollen zone P1 is devoid of pollen grains.
KK-P2 (332.5–287.5 cm) Poor in pollen	This zone is poor in pollen. The number of pollen grains is the highest at depth 322.5–315.0 cm (the horizon of decomposed peat). The slight increase in pollen frequencies of <i>Pinus sylvestris</i> -type and <i>Betula</i> undiff. occurs at this level, along with a noticeable presence of Poaceae and <i>Artemisia</i> pollen. Pollen of <i>Corylus avellana</i> , <i>Quercus</i> and <i>Picea abies</i> . is also present in trace amounts. Among spore-producing plants <i>Equisetum</i> share constitutes a prominent contribution. At some depths of this zone corroded grains constitute almost half of the entire amount of pollen.
KK-P3 (287.5–262.5 cm) Pinus-Betula-NAP	<p>The AP relative abundances lie in a range 88.4–94.6% and are composed mostly of continuous and decreasing curve of <i>Pinus sylvestris</i>-type (41.7–63.8%) and continuous and rising curve of <i>Betula</i> undiff. (25.1–39.3%). There is a continuous pollen record of <i>Corylus avellana</i> (3.6–6.7%) and almost continuous of <i>Quercus</i> (0.1–0.6%). <i>Salix</i> undiff. and <i>Alnus</i> undiff. occur regularly with a frequency up to 4.5% and 1.4%, respectively. <i>Carpinus betulus</i> curve shows a low frequency (0.1–0.2%). There are single appearances of <i>Fagus sylvatica</i>, <i>Ulmus</i> and <i>Acer</i>.</p> <p>The NAP pollen percentages vary in range 5.4–11.6%. There is a continuous presence and the highest proportion of Cyperaceae undiff. (up to 6.2%), Poaceae undiff. (up to 3.02%) and <i>Artemisia</i> pollen (up to 3.8%). Almost regular curves, but lower relative abundance, is showed also by Apiaceae undiff., Cichoriaceae undiff., <i>Cirsium</i>-type and Rubiaceae undiff. Among spore-producing plants, <i>Filicales monoete</i>, <i>Equisetum</i> and <i>Lycopodium</i> undiff. occur marginally. Among NPPs, presence of <i>Pediastrum cenobia</i> (up to 1.9%) is visible. In this group, sporadic occurrence of <i>Habrotricha angusticollis</i>, <i>Endophlyctis lobata</i> and <i>Tilletia sphagni</i> T27 was also recorded.</p> <p>Share of corroded pollen varies in a range 1.2–18.6%.</p>
KK-P4 (262.5–242.5 cm)	The uppermost sample (at a depth of 245 cm) of this zone is totally devoid of pollen. The remaining part of the zone is characterized in the following way:

<p>Pinus-Betula</p>	<p>The AP pollen frequency exceeds 90%, (maximum 98.2%). Comparing to the previous zone, <i>Pinus sylvestris</i>-type shows significant increase of pollen relative frequency (75.0–86.4%), whereas <i>Betula</i> undiff. drops down remarkably, from 16.8 to 6.5%. A continuous pollen record of <i>Corylus avellana</i> proceed from the previous zone, however there is a decrease in pollen abundance to ca. 2.4%. There is an unbroken curve of <i>Picea abies</i>, reaching 4.0%. Relative abundance of <i>Alnus</i> undiff. pollen reaches 1.4%. Moreover, some appearances (less than 1% of frequency) of <i>Quercus</i>, <i>Fagus sylvatica</i>, <i>Carpinus betulus</i>, <i>Abies alba</i> and <i>Acer</i> pollen are registered.</p> <p>In comparison to the previous zone, range of NAP pollen percentages slightly decreases to 1.8–7.4%. Proportion of Cyperaceae undiff. and <i>Artemisia</i> pollen is reduced (maximum 2.9% and 1.5%, respectively), whereas Poaceae undiff. remains on similar level as before (up to 2.8%). Slightly irregular curves are showed also by the other herb taxa: Apiaceae undiff., Cichoriaceae undiff. and Chenopodiaceae sensu stricto. Among spore-producing plants, <i>Filicales monolete</i>, <i>Equisetum</i> and <i>Lycopodium</i> undiff. occur sporadically. Among NPPs, presence of <i>Pediastrum cenobia</i> is reduced, whereas <i>Arcella arenaria/catinus</i>, <i>Habrotrocha angusticollis</i> and <i>Gelasinospora</i> sp. T1 occur marginally. Share of corroded pollen lies in a range 1.7–6.6%.</p>
<p>KK-P5 (242.5–211 cm) Pinus</p>	<p>The AP pollen percentages show the further rise: from ca. 90% to more than 95% (max. 99.2%). Pollen record of <i>Pinus sylvestris</i>-type shows continuity and high pollen percentage, increasing gradually from lower values, ca. 70%, to the maximum value of 95.9%. <i>Betula</i> undiff. curve shows an initial peak (up to 29.7%) but later stabilizes at a lower level (ca. 3.0–6.0%). A minor peak of <i>Corylus avellana</i> pollen (2.6–7.4%) can be observed. Pollen of <i>Picea abies</i> continues to be present, decreasing from 2.1% to 0.5%. Relative abundance of <i>Alnus</i> undiff. is almost continuous and exceeds 1.0%. Other arboreal taxa so-far present in trace amounts of pollen, almost disappear in this zone.</p> <p>Range of the NAP pollen percentages shows a further decrease to 0.7–4.7%, in comparison to the previous zone. Cyperaceae undiff. pollen curve almost disappears. Relative abundance of Poaceae undiff. pollen reaches 3.2%, whereas <i>Artemisia</i> is reduced to 0.7%. Very low in values (<1%) but almost regular pollen curve occurs also for some other herbaceous taxa: Apiaceae undiff., Cichoriaceae undiff., Rosaceae undiff. and Chenopodiaceae sensu stricto.</p>

	<p>Among spore-producing plants, <i>Equisetum</i> and <i>Dryopteris</i>, occurs sporadically. Among NPPs, <i>Arcella arenaria/catinus</i> and <i>Endophlyctis lobata</i> T13 continue to show in a very low abundance, whereas <i>Habrotricha angusticollis</i> reappear in the upper part of the zone.</p> <p>Share of corroded pollen varies between 4.6 and 15.2%.</p> <p>In the uppermost sample of this zone, at a depth of 212.5 cm, a sudden shift in proportion of dominant arboreal taxa occurs: relative frequency of <i>Betula</i> undiff. rises to 74.4%, whereas <i>Pinus sylvestris</i>-type drops to 11.7%. Moreover, beside a significant share of <i>Corylus avellana</i> (10.7%), small share of <i>Alnus</i> undiff. (2%) and trace amount of some other woody and herbaceous taxa, this sample is generally poor in pollen.</p>
<p>KK-P6 (211–197.5 cm) Pinus-Betula-NAP</p>	<p>The AP relative frequencies remain on a high level (max. 99.8%). <i>Pinus sylvestris</i>-type pollen curve shows a decrease to 62.6%, whereas <i>Betula</i> undiff. slightly rises to 19.1%. A noticeable peak on <i>Corylus avellana</i> curve (up to 12.1%) can be observed. Relative abundance of <i>Quercus</i> pollen increases to 4.0%. <i>Alnus</i> undiff. curve drops to 0.2%.</p> <p>The NAP pollen percentages vary in the range 0.2–4.6%. There is a noticeable rise on <i>Artemisia</i> curve up to 1.4%. Other herbaceous taxa show their pollen relative abundances below 1%, however pollen of Cyperaceae undiff., Poaceae undiff. Apiaceae undiff., Cichoriaceae undiff., Rosaceae undiff. and Chenopodiaceae sensu stricto was recorded. Noticeable is appearance of pollen (<1.0%) of different types of <i>Rumex acetosa</i> and <i>Rumex acetosella</i>.</p> <p>Spore-producing plants and NPPs taxa, except of <i>Endophlyctis lobata</i> T13, <i>Gelasinospora</i> sp. T1 and <i>Microthyrium</i> sp. T8, are not present in this zone. Relative frequency of corroded pollen varies in range 2.8–15.8%.</p>
<p>KK-P7 (197.5–142.5 cm) Pinus-NAP</p>	<p>The AP pollen percentages lie between 92.4 and 98.7% and pollen curve of <i>Pinus sylvestris</i>-type is still a dominant element, oscillating in a range 78.8–97.0%. Pollen curve of <i>Betula</i> undiff. decreases and show some minor fluctuations, approaching maximum 10.9%. <i>Quercus</i> possesses almost continuous curve with values oscillating between 0.2 and 8.0%. <i>Corylus avellana</i> is also characterized by almost unbroken curve, but with noticeably lower values (0.5–4.1%) than in the previous zones. <i>Picea abies</i> shows a continuous pollen presence, whereas pollen of <i>Salix</i> undiff. and <i>Alnus</i> undiff. is also present but more irregularly. All the three taxa, however, show relative abundancy below 1.0%. There are also rare occurrences (with relative frequencies <1.0%) of other woody taxa: <i>Ulmus</i>, <i>Fagus sylvatica</i>, <i>Abies alba</i>, <i>Carpinus betulus</i> and <i>Acer</i>.</p>

	<p>The NAP pollen percentages slightly rise and are confined within a range 1.3–7.6%. The main components of herb taxa show almost continuous pollen record in this interval and include: <i>Artemisia</i> (up to 2.8%), Cyperaceae undiff. (up to 1.7%), Poaceae undiff. (max. 1.2%), Chenopodiaceae sensu stricto (max. 1.1%) and Rosaceae undiff. (up to 1.4%). Almost unbroken curves, but with relative frequencies below 1.0%, are also exhibited by: Apiaceae undiff. <i>Rumex acetosa/R. acetosella</i> and <i>Rumex acetosella</i>-type.</p> <p>In this interval, there is also some trace proportion of spore-producing plants, and NPPs represented by <i>Microthyrium</i> sp. T8. Corroded pollen varies between 2.6 and 16.6%.</p>	
<p>KK-P8 (142.5–85 cm) Pinus-Cyperaceae</p>	<p>The AP pollen percentages remain at a level of 94.2–98.4%, similarly to the previous zone. Pollen record of <i>Pinus sylvestris</i>-type is more stable (maximum 95.3%), whereas relative abundance of <i>Betula</i> undiff. pollen decrease even more and show mean value of 2.8% (with a maximum at 7.7% in the uppermost sample). <i>Quercus</i> and <i>Corylus avellana</i>, although with some disruptions of the curves, remain at similar level. <i>Picea abies</i> (up to 2.2%), <i>Salix</i> undiff. (up to 1.4%) and <i>Alnus</i> undiff. (max. 1.0%) pollen is still mostly present. Some sporadic pollen occurrences (<1.0%) of <i>Ulmus</i> and <i>Fagus sylvatica</i> can be also observed.</p> <p>The NAP pollen frequencies also stay in a similar range (2.0–5.8%) as before, however, now the greatest proportion comes from Cyperaceae undiff. (0.2–3.0%) instead of <i>Artemisia</i> (0.2–1.4%). The latter, along with less abundant herbaceous taxa (e.g. Poaceae undiff., Apiaceae undiff. and Chenopodiaceae sensu stricto), diminishes throughout this zone.</p> <p>In case of spore-producing plants and NPPs, single occurrences of the <i>Dryopteris</i>, <i>Filicales monolete</i> and <i>Microthyrium</i> sp. T8 are continued. Corroded pollen varies in range 1.8–14.7%.</p>	
<p>KK-P9 (85–57.5 cm) Pinus-Picea-Betula</p>	<p>The AP pollen frequencies vary in range 91.6–97.9%. The most significant change in AP taxa composition concerns a steep reduction in relative frequency of <i>Pinus sylvestris</i>-type from ca. 85.0–95.0% to 37.9–48.1%. On the other hand, <i>Picea abies</i> curve is gradually rising, from ca. 11.6 to 33.3%. <i>Betula</i> undiff. curve shows only one peak (up to 32.6%) at the beginning of this zone and later stabilizes on a level of several</p>	<p>In the zones KK-P9 and KK-P10, the NAP pollen percentages remain on a level similar to the previous zone (2.1–8.4% and 2.6–6.2%, respectively). The dominant component of herb taxa is Cyperaceae undiff. (max. 4.6%), Poaceae undiff. (max. 2.4%) and Rosaceae undiff. (max. 1.4%). Among other non-arboreal taxa, some appearance of <i>Plantago lanceolata</i>, <i>Plantago media</i> and <i>Plantago major</i> were also recorded.</p>

	percents. <i>Quercus</i> shows continuous curve but low abundance (usually ca. 1.0%), whereas <i>Corylus avellana</i> curve noticeably rises to 9.6%. Moreover, in this zone the continuous pollen record of <i>Ulmus</i> and <i>Alnus</i> undiff. is observed (0.5–4.1% and 0.8–1.9%, respectively). Toward the upper boundary of this zone, also <i>Tilia</i> undiff. pollen (up to 5.8%) appears for the first time.	In the KK-P11 zone, the percentages of NAP rise to 15.4% in the uppermost sample. Also the proportions of herbaceous taxa change here: Poaceae undiff. predominates (max. 9.6%), along with Cichoriaceae undiff. (max. 4.1%), Apiaceae undiff. (max. 1.1%), <i>Artemisia</i> (max. 1.4%) and others. Presence of <i>Plantago lanceolata</i> is marked. Some new-coming taxa appear also in trace amount (<i>Stachys</i> -type, <i>Prunella</i> type, <i>Trifolium</i> undiff., <i>Veronica</i>).
KK-P10 (57.5–22.5 cm) Picea-Pinus-Tilia-Corylus	In this zone pollen curve of <i>Pinus sylvestris</i> -type continues to fall (minimum 11.8%), whereas <i>Picea abies</i> approaches 50.8%. Other woody taxa continue their regular trends also in this zone (the most abundant <i>Tilia</i> 6.1–15.4% and <i>Corylus avellana</i> 5.3%–13.8%), and moreover the unbroken curve of <i>Fagus sylvatica</i> and <i>Abies alba</i> occur for the first time (up to 2.2% and 5.6%, respectively).	Within the all three zones, spore-producing plants are mainly represented by <i>Lycopodium</i> undiff. (up to 8.1%) and/or sporadically also by <i>Filicales monoete</i> . Among NPPs there are only single occurrences of <i>Microthyrium</i> sp. T8. Curve of corroded pollen is increasing and later decreasing significantly within the two first substages of this zone (from 15.6 to max. 27.3%). In the uppermost samples of the KK-P11 zone it rises again to high proportion (maximum 24.3%).
KK-P11 (22.5–0 cm) Pinus-Picea-Abies-NAP	This zone is marked by a noticeable peak of <i>Pinus sylvestris</i> -type (maximum 56.7%, avg. 33.4%), gradual decrease of <i>Picea abies</i> curve (minimum 16.5%, avg. 22.2%) and further rise of continuous record of <i>Abies alba</i> (maximum 14.7%, avg. 12.22%). Other arboreal taxa remain at a similar level as previously.	

241

242 **Table S8.** Results of pollen analysis of the Kotoń landslide fen deposits divided into LPAZ (see pollen diagram in SM Figure S6).

LPAZ	Results of pollen analysis
KT-P1 (500–450 cm) Lack of pollen	In this zone there is a lack of pollen.
KT-P2 (450–397.5 cm) NAP-Pinus- Redeposited pollen?	<p>In the KT-P2 zone, the AP pollen percentage values show a mean of 43.78%, with a main component being <i>Pinus sylvestris</i>-type (relative abundance between 20.8 and 36.1%) and <i>Betula</i> undiff. (relative abundance between 2.0 and 9.1%). There are also single appearances of <i>Pinus cembra</i>/P. haploxylon-type, <i>Betula nana</i>-type, <i>Ephedra fragilis</i>-type, <i>Ephedra distachya</i> and <i>Juniperus</i>, with pollen frequency equal or below 1.0%. There is a continuous pollen curve of <i>Alnus</i> undiff. with maximum values of 3.4%, and almost a continuous pollen curve of <i>Picea abies</i>, <i>Abies alba</i> and <i>Salix</i> undiff. with maximum values of 5.5%, 4.9% and 1.5%, respectively. There are appearances of trace amount of pollen of <i>Fagus sylvatica</i>, <i>Carpinus betulus</i>, <i>Quercus</i>, <i>Tilia</i> undiff., <i>Ulmus</i> and <i>Populus</i>, mostly around or below 1.0%.</p> <p>The NAP pollen share shows a mean of 56.22%. There are continuous pollen curves and dominant relative abundances of Poaceae undiff. (with values in the range 11.4–27.7%), Cyperaceae undiff. (7.3–20.4%), <i>Taraxacum</i>-type (2.8–20.2%) and Apiaceae undiff. (0.7–7.3%). <i>Valeriana officinalis</i>-type has almost continuous pollen curve and relative abundances between 0.9 and 7.7%. Also continuous but of a smaller relative abundances are pollen curves of <i>Artemisia</i> and Chenopodiaceae, around 1.0% on average. Almost continuous and with a low or trace frequencies are pollen curves of <i>Ranunculus</i>, <i>Anthemis</i>-type, <i>Aster</i>-type and <i>Polygonum bistorta</i>. <i>Filipendula</i> pollen appears in the upper part of this zone.</p> <p>Among the other groups, a large share of indeterminable pollen can be noticed, from 1.3 to 5.7%, as well as abundant spores of <i>Filicales monoete</i>, with a maximum of 11.6%. There is also a continuous curve of <i>Sphagnum</i> spores, with a maximum of 1.2%.</p>
KT-P3 (397.5–327.5 cm) NAP-Pinus-Betula- Aquatic	<p>The AP pollen relative abundance is comprised within a range 32.0–50.4% (mean 39.72%). The dominant elements of arboreal taxa are <i>Pinus sylvestris</i>-type, with pollen frequencies in range 18.3–37.3% (avg. 28.12%) and <i>Betula</i> undiff. in range 3.9–10.0% (mean 7.60%). <i>Salix</i> undiff. also show continuous curve, with values in range 0.9–3.7% (mean 2.62%). Noticeably, there are several occurrences of <i>Juniperus</i> pollen below 1% and some single appearances of <i>Hippophae rhamnoides</i> and <i>Dryas octopetala</i> pollen. From the tree taxa present in the previous</p>

	<p>zone, pollen of <i>Alnus</i> undiff., <i>Populus</i> and <i>Corylus avellana</i> is still present in several samples, however at low frequencies (below ca. 1.0%).</p> <p>The NAP pollen share is slightly higher than in the previous zone, with values between 49.6 and 68.0% (mean 60.25%). The dominant components are still Poaceae undiff. which shows continuous curve and values between 10.6 and 30.4% (mean 21.85%) and Cyperaceae undiff., with values in range 14.6–39.3 (mean 21.68%). There is a prominent increase in <i>Ranunculus</i> pollen curve values, in range 1.9–9.5% (mean 5.72%). The continuous pollen curves, but of a much smaller relative abundance, belongs also to <i>Artemisia</i>, Apiaceae undiff., <i>Valeriana officinalis</i>-type, <i>Taraxacum</i>-type, <i>Anthemis</i>-type, <i>Aster</i>-type and <i>Helianthemum</i>. There is also a noticeable drop in values and the disappearance of <i>Filipendula</i> pollen. Among aquatic plants group, a noticeable rise in the <i>Potamogeton</i> pollen curve is visible, with a maximum value of 3.4%. In the upper part of this zone the <i>Menyanthes trifoliata</i> pollen curve starts to rise. Also a growth in relative abundance of <i>Pediastrum</i> cenobia up to 29.3% is confined within the boundaries of this zone.</p>
<p>KT- P4 (327.5–297.5 cm) Cyperaceae-Betula- Pinus</p>	<p>The average AP pollen frequencies show a rise from 39.72% (zone KT-P3) to 48.85% in the current zone. Pollen record of <i>Pinus sylvestris</i>-type is continuous and show fluctuating values, the lowest ca. 15.6%, to the maximum value of 40.1% (avg. 25.72%). <i>Betula</i> undiff. curve shows continuous occurrence and increased values oscillating around 10%, however in the uppermost sample (a depth of 300 cm) it exclusively shows a peak of 67.4%, the highest value in the entire Kotoń pollen record of this taxon. Simultaneously, values of the <i>Betula nana</i>-type curve rise, from 0.6% to 2.0%. <i>Salix</i> undiff. curve shows low but continuous values up to 2.0%. There are some appearances of <i>Juniperus</i> up to 1.3%. There is some trace amount of <i>Dryas octopetala</i> pollen.</p> <p>The mean percentage of NAP shows a decrease from 60.26 (the previous zone) to 51.13%. Cyperaceae undiff. pollen curve strongly fluctuates between 6.5% and 53.2%, average: 31.63%. A drop in Poaceae undiff. and <i>Ranunculus</i> pollen abundance can be noticed, from a maximum 22.1% to a minimum 3.5% and from a maximum 4.1% to a minimum 0.5%, respectively. <i>Taraxacum</i>-type and Apiaceae undiff. also show some drop in their relative abundances. <i>Artemisia</i> pollen percentage remains on a level similar to the previous zone, the same as the other herbaceous taxa. In this zone, a gradual ceasing of pollen of <i>Valeriana officinalis</i>-type is visible.</p> <p>Among spore-producing, algae and aquatic plants, there is a noticeable disappearance of <i>Potamogeton</i>, <i>Sphagnum</i> and <i>Pediastrum</i> whereas <i>Menyanthes trifoliata</i> pollen appears in significant proportion (up to 8.5%).</p>

<p>KT-P5 (297.5–267.5 cm) Pinus-Betula</p>	<p>The average AP pollen share show a further growth, this time up to 66.8% in the current zone. Pollen curve of <i>Pinus sylvestris</i>-type shows further rise, oscillating between 57.6 and 37.9%, (mean 47.65%). <i>Betula</i> undiff. curve also shows slightly increased values, minimum 9.1 and maximum 23.9% (mean 16.23%). Values of the <i>Betula nana</i>-type curve and <i>Salix</i> undiff. reach maximum 2.9 and 1.3%, respectively. There is again some appearance of <i>Juniperus</i> and <i>Dryas octopetala</i> pollen in several samples.</p> <p>The mean frequency of NAP pollen shows a decrease from 51.1 (the previous zone) to 33.2%. Cyperaceae undiff. pollen curve shows a distinct peak with a value of 30.9%. A further decrease in Poaceae undiff. pollen share is visible, whereas <i>Filipendula</i> pollen frequency is slightly more pronounced. The curves of other herbaceous taxa as well as taxa in the spore-producing plants, aquatic plants and algae show trends similar to the previous zone.</p>
<p>KT-P6 (267.5–182.5 cm) Pinus</p>	<p>The AP pollen percentages lie between 63.8% and 86.6% (mean 79.76%) and the pollen curve of <i>Pinus sylvestris</i>-type rises further, oscillating in a range 55.3–79.1%. There is also almost a continuous presence of <i>Pinus cembra</i>/<i>P. haploxyylon</i>-type, however in a small amount. Continuous pollen curve of <i>Betula</i> undiff. slightly decreases and shows some minor fluctuations, approaching max. 15.4%. Continuous pollen curve of <i>Betula nana</i>-type stays at a level similar to the previous zone, oscillating between 0.8 and 3.0%. <i>Picea abies</i> pollen appears in low amount, oscillating around ca. 1%.</p> <p>The NAP pollen percentages decrease and are confined within a range 13.4–36.1% (mean 20.24%). Cyperaceae undiff. pollen curve shows a decrease in abundance, fluctuating between 1.4% and 19.5%, on average: 9.08%. <i>Filipendula</i> show a continuous pollen curve amounting to a few percent, with a peak up to 17.4% at a depth of 211 cm. A further slight reduction in Poaceae undiff. pollen abundance is visible (maximum 4.6%). <i>Artemisia</i>, Chenopodiaceae and <i>Galium</i>-type also show continuous pollen curves with values up to ca. 1.5–3.5%. <i>Thalictrum</i>, Apiaceae undiff., <i>Ranunculus</i> show discontinuous pollen curves with very low relative abundances. <i>Valeriana officinalis</i>-type shows a slight increase in abundance only in the upper part of this zone, whereas <i>Taraxacum</i>-type shows up to 2.6% only in the lower part of this zone.</p> <p>Among the remaining groups, <i>Menyanthes trifoliata</i> pollen is still present, however discontinuously and in a very small amount (up to 2.1%). Indeterminable pollen reaches 4.7%.</p>
<p>KT-P7 (182.5–152.5 cm) Pinus-NAP</p>	<p>The AP pollen shares decrease compared to the previous zone and range between 59.1 and 67.2% (mean 63.55%). A slight drop in the share of the <i>Pinus sylvestris</i> pollen can be observed. <i>Betula</i> undiff. pollen frequency is maintained at the level similar to the previous zone (average 6.31%). Pollen of <i>Pinus cembra</i>/<i>P. haploxyylon</i>-type</p>

	<p>and <i>Betula nana</i>-type is present in a low relative abundance (1.0–3.2% and 0.1–1.4%, respectively). <i>Picea abies</i> pollen frequency is below 1.0%. <i>Salix</i> undiff. pollen curve slightly rise to the maximum 1.3%.</p> <p>The mean value of NAP pollen frequencies in this zone increases to 36.48%. Share of Poaceae undiff. pollen rise and oscillates between 4.6 and 7.8% (mean 6.18%). Cyperaceae undiff. pollen curve rises distinctively and oscillates in a range 10.7–18.9% (mean 15.10%). Similar growth can be observed for <i>Artemisia</i> and Apiaceae undiff. pollen curves (mean 5.17 and 1.97%, respectively). A slight increase in pollen relative abundance occurs also for <i>Taraxacum</i>-type and <i>Valeriana officinalis</i>-type. <i>Filipendula</i> pollen curve is continuous and stay at a similar level as previously, ranging from 1.2 to 2.6%. Small share of <i>Polygonum bistorta</i> reappears in this level. Among the other groups, a lack of <i>Menyanthes trifoliata</i> pollen is noticeable. Indeterminable pollen curve shows similar values as previously.</p>
<p>KT-P8 (152.5–117.5 cm) NAP-Pinus-Betula</p>	<p>The AP pollen relative abundances continue to fall, ranging between 44.2 and 58.8% (mean 51.25%). A further decrease in the share of the <i>Pinus sylvestris</i> pollen is visible (mean 36.75%). <i>Betula</i> undiff. pollen frequency is slightly higher than in the previous zone (mean 8.90%). <i>Pinus cembra</i>/<i>P. haploxylon</i>-type and <i>Betula nana</i>-type pollen frequencies remain at a similar level as previously. <i>Picea abies</i> and <i>Salix</i> undiff pollen frequencies are below 1.0%.</p> <p>NAP pollen shares show mean of 51.25%. Frequency of Poaceae undiff. pollen increase noticeably and oscillates between 7.1 and 13.8% (mean 10.22%). Cyperaceae undiff. pollen curve rises distinctively and varies between 17.6 and 36.2% (mean 26.57%). <i>Artemisia</i> and Apiaceae undiff. pollen curves show peaks with maximum values of 7.5 and 7.0%, respectively. A slight increase in relative abundance occurs also for <i>Taraxacum</i>-type, <i>Filipendula</i>, <i>Valeriana officinalis</i>-type, <i>Thalictrum</i> and Chenopodiaceae pollen curves continue to occur at the similar level as in the previous zone.</p> <p>Among other groups, beside the indeterminable pollen curve remaining at the similar level as previously, there is an absence of other taxa pollen/spores.</p>
<p>KT-P9 (117.5–85 cm) Pinus-Picea</p>	<p>The AP pollen frequencies, in comparison to the previous zone, show a large increase to 74.7–88.1% (mean 81.20%). After a short initial rise to a maximum 61.7%, the <i>Pinus sylvestris</i>-type curve starts to fall. Pollen frequency of <i>Betula</i> undiff. remains at the level of a few percents (2.1–7.2%). <i>Betula nana</i>-type pollen curve is ceasing towards the end of the zone. Several arboreal pollen curves show continuity and distinctive increase in</p>

	<p>values: <i>Alnus</i> undiff. to 1.5%, <i>Picea abies</i> to 17.8%, <i>Tilia</i> undiff. to 1.5%, <i>Ulmus</i> to 7.6% and <i>Corylus avellana</i> to 4.6%.</p> <p>The proportion of NAP pollen is much lower than for the previous LPAZ and equals 18.78%. Most pollen curves of the herbs show decreasing trend, only <i>Taraxacum</i>-type and <i>Filipendula</i> show some noticeable values, with a maximum 4.7 and 7.6%, respectively. Among spore-producing plants, there is a distinctive increase in the proportion of <i>Filicales monoete</i> spores (values varies between 4.6 and 29.9%).</p>
<p>KT-P10 (85–62.5 cm) Picea-Corylus</p>	<p>The AP pollen percentage rises further and reaches 94.8%. <i>Pinus sylvestris</i>-type curve falls to 16.1%. Pollen frequency of <i>Betula</i> undiff. is low (0.5–2.0%) and the curve is disrupted. Several arboreal pollen curves further show regularity and rising frequencies: <i>Alnus</i> undiff. to 10.1%, <i>Picea abies</i> to 30.4%, <i>Tilia</i> undiff. to 9.4%, <i>Ulmus</i> to 6.9% and <i>Corylus avellana</i> to 21.2%. An almost continuous pollen curve (however of values below 1%) can be noticed also for <i>Quercus</i> and <i>Populus</i>.</p> <p>The NAP pollen frequency shows a further huge decrease in comparison to the previous zone, 5.16% on average. Among spore-producing plants, <i>Filicales monoete</i> spores share remains on high level (17.3% on average).</p>
<p>KT-P11 (62.5–25 cm) Abies-Picea</p>	<p>The AP values remain on a high level at the beginning of this zone (maximum 93.7%, avg. 74.41%), but later they gradually decrease to 76.9%. <i>Pinus sylvestris</i>-type pollen curve remains constant around the mean value of 13.18%. <i>Betula</i> undiff. pollen curve stays at the level of a few percent. <i>Picea abies</i> pollen curve decreases from 15.1 to 3.3%. <i>Alnus</i> undiff. pollen curve reaches maximum of 10.1%. <i>Populus</i>, <i>Corylus avellana</i>, <i>Ulmus</i> and <i>Tilia</i> undiff. show continuous pollen curve, however the drop above the depth of 62.5 cm in their pollen relative abundances is visible. <i>Quercus</i> and <i>Carpinus betulus</i> have continuous pollen curves, with maximum values at 1.9 and 0.9% respectively. <i>Fagus sylvatica</i> and <i>Abies alba</i> show a prominent rise in their pollen frequency, with maximum values at 3.9 and 44.4%, respectively.</p> <p>Mean relative frequencies of NAP pollen increase to 11.4% in this zone. Pollen curves of Apiaceae undiff. and <i>Ranunculus</i> show a slight rise in values, <i>Filipendula</i> curve also but in the upper part of this zone. <i>Filicales monoete</i> continue to predominate.</p>
<p>KT-P12 (25–0 cm) NAP-Fagus-Betula</p>	<p>The AP pollen relative frequencies decrease in this zone, yielding 55.5% on average. <i>Pinus sylvestris</i>-type and <i>Betula</i> undiff. pollen curves show some peaks (25.1 and 14.0%, respectively). <i>Alnus</i> undiff. curve remains on the similar level as previously, whereas <i>Picea abies</i> show value ca. 5.7%. <i>Populus</i>, <i>Corylus avellana</i>, <i>Ulmus</i> and <i>Tilia</i> undiff. relative frequencies are ceasing. <i>Quercus</i> and <i>Carpinus betulus</i> curves rise slightly only in the uppermost</p>

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46

243

samples. *Fagus sylvatica* pollen share show culmination of 8.6%, whereas previously high pollen share of *Abies alba* decreases from 21.6 to 0.2% in the uppermost sample.

Comparing to the previous zone, the NAP pollen frequencies increase further, up to 59.0% in the uppermost sample. Poaceae undiff. and Cyperaceae undiff. pollen curves rise simultaneously. Among other herb taxa, *Aster*-type, *Plantago lanceolata* and *Triticum*-type, *Potentilla*-type and Rosaceae undiff. pollen relative abundances also show an increase. Share of *Filicales monoete* spores decreases from 32.5 to 1.0%.

For Peer Review

1
2
3 244 **Palaeoecological stages of the Klaklowo landslide fen development from ca. 13,900 to ca.**

4
5 245 **10,000 cal BP**

6
7 246 Stages of palaeoecological development of the Klaklowo fen are presented in Figure 4 and

8
9 247 Figure 6. Additionally, the selected representative plant taxa in time domain are shown in

10
11 248 Figure 7.

12
13
14 249

15
16 250 ***Stage KK-3a and 3b (307.5–267.5 cm, from ca. 13,870 ± 54 to ca. 13,620 ± 39 cal BP, ca.***

17
18 251 ***250 years) Colonization and overgrowing of waterbody II/ Betula-dominated boreal forest***

19
20 252 A detail palaeoecological interpretation of this stage was presented in Pilch et al. (2025b).

21
22 253 Klaklowo waterbody II was characterized by minerogenic sedimentation (clayey silt, Figure 3

23
24 254 C and Figure 6, zone KK-L1) and the co-occurrence of macrophytes predominated by

25
26 255 Characeae meadows and intense precipitation of calcium carbonate resulting from alkaline

27
28 256 conditions (Figure 4 and Figure 6). Aquatic vegetation succession in waterbody was followed

29
30 257 by the expansion of *Betula* sect. *Albae* and *Betula* sect. *Nanae* species in the surrounding area.

31
32 258 This phenomenon can be also observed in the pollen data. Although the lower part of this

33
34 259 stage covers the deposits poor in pollen (SM Figure S5 and Figure 6, LPAZ KK-P2, see in

35
36 260 Pilch et al. (2025b) for explanation of pollen depletion), the upper part (LPAZ KK-P3) is

37
38 261 characterized by predominance of pollen of pioneering arboreal taxa (decreased curve of

39
40 262 *Pinus sylvestris*-type and increased curve of *Betula* undiff.) and noticeable contribution of

41
42 263 NAP pollen (Cyperaceae undiff., Poaceae undiff. and *Artemisia*). Therefore, a transition from

43
44 264 more open-land to *Betula*-dominated boreal forest succession and overgrowing of the

45
46 265 Klaklowo waterbody II, presumably associated with climatic warming of GI-1c/ Allerød, was

47
48 266 recorded during the stage KK-3.

49
50 267

51
52

53
54

55
56

57
58

59
60

1
2
3 268 ***Stage KK-4 (267.5–217.5 m, from ca. 13,620 ± 39 to ca. 13,200 ± 82 cal BP, ca. 420 years)***

4
5 269 ***Long-lasting fen - wetter conditions and moss fen peat accumulation /Pinus-Larix-Betula***

6
7
8 270 ***boreal forest***

9
10 271 This stage lasted ca. 420 years and documents the formation of the long-lasting Klaklowo fen,

11
12 272 during which the accumulation of moss fen peat replaces the earlier minerogenic

13
14 273 sedimentation, yielding up to ca. 80% values on the LOI curve (the highest in the entire

15
16 274 Klaklowo sequence, Figure 3 C, zone KK-L2). The most striking feature of this zone is the

17
18 275 local presence and expansion of arboreal taxa, reflected in abundant macrofossils of *Pinus*

19
20 276 *sylvestris*, *Larix decidua* and Coniferae, as well as *Betula pubescens* (however the number of

21
22 277 the latter one is declining in the upper part of this zone) (Figure 4 and Figure 6). Dwarf shrubs

23
24 278 and shrubs of *Betula* sect. *Nanae* could be, therefore, outcompeted for light access, and

25
26 279 declined in number. Moreover, macrofossils of *Populus tremula* and *Sorbus aucuparia*

27
28 280 indicate the growing diversity of woody taxa. Abundant leaves fragments (undiff.) confirm

29
30 281 the development of trees and shrubs in the Klaklowo fen area. The observed changes in

31
32 282 macrofossil composition are in agreement with the pollen data: there is a dominance of *Pinus*

33
34 283 *sylvestris*-type pollen and decreasing share of *Betula* undiff. pollen at the beginning of stage

35
36 284 KK-4 (SM Figure S5, LPAZ KK-P4) and further increase in *Pinus sylvestris*-type pollen

37
38 285 percentage in the LPAZ KK-P5. Climate warming should be considered as an important

39
40 286 factor enhancing pollen productivity (Feurdean et al., 2007). The so-far dominant mire plants

41
42 287 are still present, however, reduced in number (*Carex rostrata*, *Carex diandra*, Bryopsida)

43
44 288 (Figure 4 and Figure 6). This is also reflected in the decline in Cyperaceae undiff. pollen

45
46 289 curve (SM Figure S5, LPAZ KK-P5). Wet conditions in the fen, possibly in the form of small

47
48 290 water pools and fluctuating water level, are indicated by the presence of aquatic taxa

49
50 291 (*Characeae*, *Hippuris vulgaris*, Ostracoda, *Daphnia* sp., Porifera etc.).

1
2
3 292 During the stage KK-4, at a depth of ca. 240–242.5 cm, a thin minerogenic intercalation
4
5 293 could be noticed (moreover, in the sediment core intended for LOI analysis a huge piece of
6
7 294 wood occurred in this sample), whereas at a depth of 245 cm (the uppermost sample of LPAZ
8
9
10 295 KK-P4) there is a total lack of pollen, which could be explained by pre-depositional oxidation
11
12 296 of pollen and later redeposition of such pollen-sterile sediment into the Klaklowo fen (Carrión
13
14 297 et al., 2009).

15
16 298
17
18
19 299 ***Stage KK-5a (217.5–167.5 cm, from ca. 13,200 ± 82 to ca. 12,320 ± 122 cal BP, ca. 880***
20
21 300 ***years) Long-lasting fen – less wet conditions and more minerogenic delivery/ Pinus-Larix-***
22
23 301 ***Betula boreal forest***

24
25 302 Stage KK-5a lasted ca. 880 years and constitutes a record of the further development of the
26
27 303 long-lasting Klaklowo fen, this time characterized by a noticeable and continuous delivery of
28
29 304 minerogenic material accompanying the peat accumulation in a somewhat less wet conditions
30
31 305 in the fen, mainly woody osier peat and later also moss fen peat (LOI curve values of ca. 45–
32
33 306 65%, Figure 3 C, zone KK-L3). At the beginning of the stage KK-5a there is a noticeable
34
35 307 minerogenic insert resulting in a drop to ca. 7% on the LOI curve between 217.5 and 207.5
36
37 308 cm. It corresponds to a decreased share of needle fragments of *Pinus sylvestris* and Coniferae
38
39 309 bud scales, however, *Larix decidua* macrofossils are present abundantly (Figure 4 and Figure
40
41 310 6). Fruits and fruit scales of *Betula nana* are almost absent, whereas of *Betula pubescens* and
42
43 311 *Betula* sect. *Albae* are smaller in number. Several bud scales of *Populus tremula* appear in this
44
45 312 interval. Among other plant taxa there is a single occurrence of *Carex rostrata*, some
46
47 313 Bryopsida stems and *Filipendula ulmaria* fruits. Among animal remains, Ostracoda, Oribatid
48
49 314 mites and Trichoptera larval cases are present. This mineral horizon is also reflected in the
50
51 315 pollen data. At the end of the LPAZ KK-P5 (SM Figure S5), at a depth of 212.5 cm, a rapid
52
53 316 reversal in relative pollen abundances of *Pinus sylvestris*-type (a drop to 11.7%) and *Betula*

1
2
3 317 undiff (a rise to 74.4%), along with an increased amount of corroded pollen, may signalize
4
5 318 some short climatic event.

6
7 319 Above the mineral horizon, macrofossil data suggests that the area of the fen and its
8
9
10 320 surroundings continued to be covered with trees and shrubs, dominated by (with some
11
12 321 fluctuations) *Pinus sylvestris*, *Larix decidua*, Coniferae and to a lesser extent by *Betula*
13
14 322 *pubescens* and *Betula* sect. *Albae*. *Betula nana* appears less commonly. Fragments of leaves
15
16 323 (undiff.) are numerous. A significant change can be noticed in the mire plant compositions:
17
18 324 Bryopsida stems are continuously present throughout the zone, whereas there is an almost
19
20 325 total lack of *Carex rostrata* macrofossils along with the other taxa of sedges, indicating less
21
22 326 wet conditions within the fen during this stage. Continued presence of *Caltha palustris* seeds
23
24 327 and *Filipendula ulmaria* fruits together with the absence of aquatic organisms (except for the
25
26 328 marginal number of Ostracoda shells) seem to confirm this interpretation.

27
28
29
30
31 329 Similar signal can be found in the pollen data of this zone, encompassing LPAZ KK-
32
33 330 P6 and a part of KK-P7 (SM Figure S5). LPAZ KK-P6 was distinguished as a 'transition
34
35 331 zone'. It is characterized by small fluctuations of *Pinus sylvestris*-type and *Betula* undiff.
36
37 332 curves, likely reflecting some short-term climatic event. Besides the continued apparent local
38
39 333 presence (or redeposition?) of *Corylus avellana*, also *Quercus* pollen curve shows an increase
40
41 334 in values, whereas *Alnus* undiff. pollen relative abundance is noticeably decreased. The latter
42
43 335 two taxa may imply a slight drying of the surrounding habitats. These processes can be also
44
45 336 suggested by a more abundant pollen of *Artemisia* and other herbs, as well as disappearance
46
47 337 of spore-producing plants and some of NPPs taxa. In the zone KK-P7 some features of the
48
49 338 previous transition zones are continued. Definitely, *Pinus*-dominated boreal forest was locally
50
51 339 present, although some fluctuations of *Pinus sylvestris*-type curve is visible. There is only a
52
53 340 slight rise in the values of NAP curve, however the continuous curve and elevated values of
54
55 341 the pollen relative abundance of *Artemisia* can be noticed.

1
2
3 342
4
5 343 **Stage KK-5b (167.5–127.5 cm, from ca. 12,320 ± 122 to ca. 11,240 ± 92 cal BP, ca. 1080**
6
7 344 **years): Long lasting fen – Wetter conditions (moss fen peat accumulation) and later less**
8
9 345 **wet conditions (total disappearance of Bryopsida)/ Larix-Pinus-Betula boreal forest**
10
11
12 346 Stage KK-5b lasted ca. 1080 years, and shows a distinct division into two substages, reflected
13
14 347 in lithological (Figure 3 C and Figure 6, zones KK-L4 and KK-L5) and macrofossil data
15
16 348 (Figure 4 and Figure 6, LMAZ KK-M13 and KK-M14). Zone KK-L4 is represented by pure
17
18 349 moss fen peat accumulation showing reduced contamination by minerogenic matter and high
19
20 350 LOI values, up to ca. 75 %. LMAZ KK-M13 is characterized by a decreasing number of
21
22 351 needles fragments of *Pinus sylvestris*, abundant needles of *Larix decidua*, marginal amount of
23
24 352 Coniferae bud scales and single occurrences of macrofossils of *Betula pubescens* and *Betula*
25
26 353 *nana*. Mire plants are represented by the numerous macroremains of Bryopsida, and there is
27
28 354 some reappearance of fruits and urticles of *Carex rostrata*.

29
30
31
32
33 355 In the KK-L5 zone, moss fen peat continues to occur, however, on the LOI curve a
34
35 356 gradual decrease from ca. 55% to ca. 35% can be noticed, reflecting an increasing
36
37 357 minerogenic delivery. The corresponding LMAZ KK-M14 shows traits similar to the previous
38
39 358 LMAZ, with a difference in a higher number of *Betula pubescens* fruits, several leaf
40
41 359 fragments of *Salix* sp. determined in the uppermost sample and abundant undeterminable leaf
42
43 360 fragments (also of *Salix* sp.?). Further discrepancy concerns the number of macrofossils of
44
45 361 *Carex rostrata* and Bryopsida stems diminished to trace amounts. There is also some small
46
47 362 signal of aquatic conditions (*Batrachium* sp., Ostracoda).

48
49
50
51 363 Stage KK-5b corresponds to the upper part of the above-mentioned LPAZ KK-P7 (SM
52
53 364 Figure S5) which is interpreted as *Pinus*-dominated boreal forest but with some influence
54
55 365 from the open-space herbaceous taxa and some small part of the LPAZ KK-P8 (described in
56
57 366 detail in the next palaeoecological stage).

1
2
3 367
4
5
6 368 ***Stage KK-6 (127.5–80 cm, from ca. 11,240 ± 92 to ca. 11,120 ± 99 cal BP, ca. 120 years)***

7
8 369 ***Sedge peat, minerogenic layer and woody birch peat accumulation – at a rate of ca. 4.20***
9
10 370 ***mm year⁻¹/ open space with *Pinus-Betula-Larix* tree stands***

11
12
13 371 Stage KK-6 is characterized by the highest sedimentation rate within the whole analysed
14 372 sequence of the Klaklowo fen, amounting to ca. 4.20 mm year⁻¹ – almost 50 cm of deposits of
15
16 373 this interval was accumulated within a time period of only ca. 120 years. Despite that fact,
17
18 374 these deposits vary throughout the stage. Within the zone KK-L6 (Figure 3 C), first sedge peat
19
20 375 contaminated with minerogenic material was deposited, yielding the decrease in LOI values
21
22 376 from 50% to ca. 30% and later it was overlaid by a minerogenic layer (clayey silt, 112.5–97.5
23
24 377 cm) resulting in a drop to ca. 15% on the LOI curve.

25
26
27 378 In the macrofossil data, stage KK-6 is expressed as the many prominent changes in
28
29 379 taxa abundance and composition (Figure 4 and Figure 6). There is almost a total
30
31 380 disappearance of *Pinus sylvestris* and a great reduction of the number of *Larix decidua*
32
33 381 needles and Coniferae bud scales to sporadic occurrences. Macrofossils of *Betula nana*,
34
35 382 *Betula* sect. *Nanae*, *Betula* sect. *Albae* and *Betula* sp. are present in small amounts in some
36
37 383 samples of this interval, whereas macrofossils of *Betula pubescens* are recorded continuously,
38
39 384 mostly also in small quantities. Leaf scars are continuously present throughout this zone.
40
41 385 Sedges are represented by the new-coming taxa: *Carex nigra* and *Carex canescens*. Within
42
43 386 the minerogenic layer, there are numerous sclerotia of *Cenococcum geophilum*.

44
45 387 Above the minerogenic layer, woody birch peat is accumulated (values on LOI curve
46
47 388 grow from around 20% to ca. 30%, Figure 3 C, lower part of the zone KK-L7). Organic
48
49 389 accumulation is also expressed in more diverse composition of plant macrofossils of the
50
51 390 corresponding LMAZ KK-M16 (Figure 4 and Figure 6), in both trees, shrubs and dwarf
52
53 391 shrubs group (*Pinus sylvestris*, *Larix decidua*, *Abies alba*, Coniferae, *Betula nana*, *Betula*

392 *pubescens*; *Populus tremula*, leaf scars) and in the mire plants group (*Valeriana*
393 *simplicifolia/dioica*; *Thelypteris palustris*, *Phragmites australis*, *Filipendula ulmaria*, *Carex*
394 *canescens*, *Carex nigra*).

395 Pollen spectrum in this stage shows only minor changes (SM Figure S5, LPAZ KK-P8).
396 *Pinus sylvestris*-type pollen remains prevailing, however there is a slight fall of relative
397 frequency of *Betula* undiff. pollen. *Quercus* and *Corylus avellana*, and to a lesser degree also
398 *Picea abies*, *Salix* undiff. and *Alnus* undiff., tend to show an apparent regional and/or local
399 presence. As the NAP composition slightly changes to be Cyperaceae-dominated, possible
400 reduction in dry and open-space area took place, whereas locally more wet environment
401 developed.

403 ***A part of the stage KK-7 (80–68.5 cm, from ca. 11,120 ± 99 cal BP to ca. 10,005 ± 283 cal***
404 ***BP: The beginning of accumulation of minerogenic cover on the woody birch peat***

405 Stage KK-7 shows the lowest sedimentation rate of the whole investigated depth section: 0.10
406 mm year⁻¹. The deposits of this part of the stage KK-7 are composed of woody birch peat
407 with the contamination of minerogenic material increasing from the depth 80 to 65 cm (values
408 on LOI curve show maximum around 35% and later diminishes to ca. 20%) and signaling
409 the beginning of accumulation of minerogenic cover (Figure 3 C, upper part of the zone KK-
410 L7). In the macrofossil data the further great compositional changes take place (Figure 4 and
411 Figure 6). There is a noticeable presence of *Sambucus racemosa* and *Rubus idaeus* and trace
412 amount of *Betula pubescens* and *Betula* sp. There is also a large number of macrofossils of
413 *Scirpus sylvaticus* (also redeposited?) and sclerotia of *Cenococcum geophilum*. This stage
414 coincides also with LPAZ KK-P9, separated from the previous LPAZ by the supposed hiatus
415 at a depth of ca. 85 cm (SM Figure S5 and Figure 6). The possible corresponding hiatus could
416 be also interpreted from the macrofossil data at 80 cm (Figure 4), its occurrence cannot be,

1
2
3 417 however, entirely confirmed due to the insufficient number of radiocarbon dates at this depth
4
5 418 level.

6
7 419 At the depth of the supposed hiatus, pollen data shows fundamental changes in plant
8
9 420 formations. Firstly, pollen curve of *Pinus sylvestris*-type steeply decreases (from ca. 85–95%
10
11 421 to 38–48%). Simultaneously, relative abundances of several arboreal taxa start to rise and
12
13 422 develop into continuous curves: *Picea abies* (dominating), *Ulmus*, *Alnus* undiff. and later also
14
15 423 *Tilia* undiff. These changes in pollen record reflect the disappearance of boreal forest in the
16
17 424 warming climate of the Holocene, and expansion of coniferous and deciduous trees forming
18
19 425 mixed forest. In the Klaklowo sedimentary basin, this climatic change is also reflected in
20
21 426 enhanced input of corroded pollen (within the depth extent of minerogenic cover of the
22
23 427 Klaklowo sediment sequence).
24
25
26
27
28
29

30 429 **Palaeoecological stages of the Kotoń landslide fen development from ca. 13,900 to ca.**
31
32 430 **10,000 cal BP**

33
34
35 431 Stages of palaeoecological development of the Kotoń fen are presented in Figure 5 and Figure
36
37 432 6. Additionally, the selected representative plant taxa in time domain are shown in Figure 7.
38
39

40 433
41
42 434 ***Stage KT-3 (367.5–345 cm, from ca. 13,900 ± 56 to ca. 13,820 ± 68 cal BP, ca. 80 years)***

43
44 435 ***Calcareous extremely rich fen /steppe-tundra***

45
46 436 A detail palaeoecological interpretation of this stage can be found in Pilch et al. (2025a). The
47
48 437 stage KT-3 documents a transition from the oligo-mesotrophic lake to the (calcareous)
49
50 438 extremely rich fen (Hájek et al., 2006) as a result of autogenic succession. The dominant plant
51
52 439 taxa are Bryopsida and sedges (Figure 5), what results in the moss fen peat accumulation and
53
54 440 a rise of the LOI curve values from ca. 20 to 65% (Figure 3 C, zone KT-L4). Stage KT-3
55
56 441 corresponds to the upper part of the LPAZ KT-P3 (SM Figure S6) which is characterized by
57
58
59
60

1
2
3 442 predominance of NAP pollen (Poaceae undiff., Cyperaceae undiff., *Ranunculus* and others),
4
5 443 suggesting more open-space habitats (e.g. steppe-tundra), and only secondarily by *Pinus*
6
7 444 *sylvestris*-type and *Betula* undiff. pollen which represent arboreal taxa. There is also a
8
9 445 noticeable share of pollen/cenobia from aquatic organisms (*Potamogeton*, *Menyanthes*
10
11 446 *trifoliata* and *Pediastrum*) confirming the existence of some water pools and waterlogged
12
13 447 conditions locally in the Kotoń fen depression.
14
15
16

17 448
18
19 449 ***Stage KT-4a and b (345–300 cm, from ca. 13,820 ± 68 to ca. 13,500 ± 115, ca. 320 years)***

20
21 450 ***Moderately rich fen/ Betula boreal forest***

22
23
24 451 A detail palaeoecological interpretation of the stages KT-4a and b, which in total lasted ca.
25
26 452 320 years, is presented in Pilch et al. (2025a). The lower part of this interval shows LOI
27
28 453 values at first decreasing from ca. 65% to ca. 30% in a result of minerogenic matter admixture
29
30 454 to the woody alder peat, whereas in the upper part, LOI curve starts rising again reaching
31
32 455 values slightly over 85% as a result of almost pure uncontaminated moss fen peat
33
34 456 accumulation (Figure 3 C, zone KT-L5). The vegetation of the Kotoń moderately rich fen
35
36 457 (Hájek et al., 2006) is dominated by Bryopsida, increased share of sedges (mostly *Carex*
37
38 458 *diandra* and *Carex rostrata*), *Menyanthes trifoliata*, and sporadically by other mire plant
39
40 459 species (Figure 5 and Figure 7). Furthermore, during this stage *Betula pubescens* (and to a
41
42 460 lesser extent also *Betula nana*) start to spread in the fen area, likely in response to the
43
44 461 warming climate. In the substage KT-4b it is followed by the appearance of *Pinus sylvestris*
45
46 462 and possibly other Coniferae species, however, due to a low number of their macrofossils the
47
48 463 *in situ* presence of the well-developed birch-pine boreal forest at that time should be
49
50 464 interpreted with some caution. On the other hand, macrofossils of species presently growing
51
52 465 in the shrub layer of the *Pinus sylvestris* light taiga, *Juniperus communis* and *Rubus saxatilis*,
53
54 466 were also identified in the substage KT-4b and may support such an interpretation.
55
56
57
58
59
60

1
2
3 467 Stage KT-4a and 4b corresponds to the ending of LPAZ KT-P3 and to the entire LPAZ
4
5 468 KT-P4 which is characterized by a slight increase of the mean AP pollen frequencies,
6
7 469 represented by *Pinus sylvestris*-type and *Betula* undiff. (SM Figure S6). The latter taxon in the
8
9 470 uppermost sample (a depth of 300 cm) exclusively shows a peak of 67.4%, the highest value
10
11 471 in the entire Kotoń pollen record. Diminished proportion of NAP pollen is dominated by
12
13 472 strongly fluctuating share of Cyperaceae undiff. pollen, what stay in agreement with the
14
15 473 abundance of *Carex* sp. fruits and urticles observed in the macrofossil data. Moreover, a slight
16
17 474 reduction in the relative frequencies of Poaceae undiff. and *Ranunculus* can be observed,
18
19 475 probably signaling recession of more open-space habitats in favor of woodland expansion.
20
21 476 Except for the *Menyanthes trifoliata* pollen, the other aquatic taxa withdrew during this stage,
22
23 477 indicating the development of some less wet local conditions in the fen comparing to the
24
25 478 previous stages and substages.
26
27
28
29
30
31
32

33 480 ***Stage KT-5a (300–185 cm, from ca. 13,500 ± 115 to ca. 11,890 ± 104 cal BP, ca. 1610***
34
35 481 ***years) Long-lasting fen – less dry conditions and more minerogenic delivery/ Betula-Pinus***
36
37 482 ***boreal forest***
38
39

40 483 Stage KT-5a documents the ongoing development of the long-lasting Kotoń fen (at this point
41
42 484 a term ‘rich-fen’ is not used anymore due to the lack of detail analysis of Bryopsida
43
44 485 composition for the depth section 300–0 cm) and resulting accumulation of ca. 125 cm peat
45
46 486 sequence (moss fen peat, sedge peat and woody osier peat) accompanied by enhanced
47
48 487 minerogenic material delivery (Figure 3 C, zones KT-L6, L7 and L8). The sedimentation rate
49
50 488 of this interval is low, ca. 1.01 and ca. 0.64 mm year⁻¹, and the overall duration of the stage
51
52 489 can be estimated at ca. 1610 years. The characteristic feature of this stage is an almost
53
54 490 continuous record of the needle fragments of *Pinus sylvestris* and Coniferae bud scales and
55
56 491 numerous macrofossils of *Betula pubescens*, presumably indicating the establishment of the
57
58
59
60

1
2
3 492 *Betula-Pinus* boreal forest in the fen vicinity (Figure 5 and Figure 6). This is also reflected in
4
5 493 the pollen data within the LPAZ KT-P5 and KT-P6 (SM Figure S6), which shows the
6
7 494 increasing relative abundance of AP pollen, dominated by *Betula undiff.* and *Pinus sylvestris-*
8
9 495 type (KT-P5) and reflecting even further expansion of *Pinus sylvestris*-type, reaching
10
11 496 maximum pollen abundance of the entire Kotoń sequence (KT-P6). Other arboreal species
12
13 497 constituting the components of the trees, shrubs and dwarf shrubs cover includes single
14
15 498 macrofossils occurrences of *Picea abies*, *Salix* sp., *Rubus* cf. *sulcatus* and *Betula nana*.
16
17 499 Correspondingly, during LPAZ KT-P6 some noticeable pollen record (however of small or
18
19 500 marginal values) of *Betula nana*-type, *Picea abies* and *Salix* undiff. can be observed. In the
20
21 501 LPAZ KT-P6 also the continuous pollen record of *Pinus cembra*/*P. haploxylon*-type appears.
22
23 502 Furthermore, in the upper part of the stage KK-5a trace amount of *Larix decidua* needles
24
25 503 occur (Figure 5).

26
27 504 Mire plants are represented by a high amount of Bryopsida stems (only in the
28
29 505 uppermost part of the LMAZ KT-M9 they disappear) and numerous macrofossils of *Carex*
30
31 506 *diandra*, *Carex nigra* and later also of *Carex canescens* (Figure 5). Number of *Carex rostrata*
32
33 507 macrofossils is strongly reduced. In the lower part of this stage there are also frequent seeds of
34
35 508 *Stellaria palustris* and some seeds of *Menyanthes trifoliata*, indicating fluctuating water level
36
37 509 (in contrast to the drier upper part of this stage). Moreover, at some depths macrofossils of
38
39 510 *Scirpus sylvaticus* and *Caltha palustris* occur sporadically. Numerous larval cases of
40
41 511 Trichoptera are also characteristic for this zone.

42
43 512 Among plants of fresh and moist habitats, there is a single fruit of *Potentilla* cf. *crantzii*,
44
45 513 possibly suggesting some arctic/alpine conditions of the surrounding habitats, however,
46
47 514 judging by the lowered relative frequency of herbs pollen during LPAZ KT-P6, the open-
48
49 515 space landscape was highly reduced during the KT-5a stage in favour of the forested area.

50
51 516

1
2
3 517 ***Stage KT-5b (185–125 cm, from ca. 11,890 ± 104 cal BP to ca. 11,260 ± 263, ca. 630 years)***

4
5 518 ***Long lasting fen – Wetter conditions (moss fen peat accumulation) and later drier***

6
7 519 ***conditions (total disappearance of Bryopsida)/ Pinus-Larix boreal forest, later open space***

8
9 520 ***with tree stands***

10
11
12 521 Stage KT-5b lasted ca. 630 years (sedimentation rate mostly ca. 0.98 mm year⁻¹, Figure 2)

13
14 522 and shows a distinct division into two parts reflected in corresponding lithological (Figure 3

15
16 523 C, KT-L9 and KT-L10), macrofossil (Figure 5, KT-M10, KT-M11) and pollen (SM Figure

17
18 524 S6, KT-P7, KT-P8) units. The lower part coincides with the almost pure moss fen peat

19
20 525 accumulation yielding very high LOI values, up to 70%, however, above the depth of ca. 170

21
22 526 cm it starts to decrease (at first to ca. 50%.) due to delivery of minerogenic matter (Figure 3

23
24 527 C, zone KT-L9). There is a visible change in macrofossils abundances (LMAZ KT-M10): the

25
26 528 number of *Larix decidua* needle fragments rises significantly, whereas fragments of leaves

27
28 529 (undiff.) disappear totally and macrofossils of *Betula pubescens* are strongly reduced. These

29
30 530 changes can signalize some opening of the forest and reduction of vegetation cover and - what

31
32 531 is also expressed in the pollen data (LPAZ KT-P7, SM Figure S6) - as an increase of NAP

33
34 532 pollen relative abundance (Poaceae undiff., *Artemisia*, Apiaceae undiff. and others) and

35
36 533 decrease of *Pinus sylvestris*-type pollen share. Furthermore, there is a single seed of *Picea*

37
38 534 *abies* and a single fruit of *Juniperus communis* found in LMAZ, confirming the occurrence of

39
40 535 this species in the Kotoń fen vicinity. The accumulation of almost pure moss fen peat is also

41
42 536 reflected in the composition of mire plants (a high amount of Bryopsida stems as well as

43
44 537 *Carex rostrata* and *Carex canescens* macrofossils) (Figure 5). Some traces of aquatic

45
46 538 conditions can be inferred from the presence of *Daphnia* sp. ehippia, whereas yet another

47
48 539 finding of the arctic/alpine *Potentilla* cf. *crantzii* fruit somehow stay in accordance with the

49
50 540 expansion of herbs observed in the pollen record.

1
2
3 541 The upper part of the stage KT-5b is characterized by continuation of minerogenic
4
5 542 material input into the sedge-moss fen peat (LOI values remain fluctuating around ca. 35–
6
7 543 45%, Figure 3 C, zone KT-L10). Plant macrofossil data shows decline of many of so-far
8
9 544 present taxa (LMAZ KT-M11, Figure 5): *Pinus sylvestris*, Coniferae, Bryopsida and *Larix*
10
11 545 *decidua*, whereas others are reduced in number and reappear only shortly (*Betula pubescens*,
12
13 546 *Carex rostrata*). Apparently undisturbed species is *Carex canescens*. This substage coincides
14
15 547 with the LPAZ KT-P8 (SM Figure 5), in which the further growing share of NAP pollen
16
17 548 (Poaceae undiff., *Artemisia*, Apiaceae undiff.) can be noticed, whereas pollen relative
18
19 549 frequency of *Pinus sylvestris*-type continues to fall. Moreover, *Betula* undiff. curve shows a
20
21 550 slight rise, whereas increased pollen share of Cyperaceae undiff. stay in accordance with plant
22
23 551 macrofossils findings.
24
25
26
27
28
29
30

31 553 ***Stage KT-6 (125–117.5 cm, from ca. 11, 260 ± 263 to ca. 10,990 ± 432 cal BP, ca. 270***
32
33 554 ***years) Minerogenic material delivery***
34
35

36 555 This stage consists of a thin interval within which LOI values show one of the most abrupt
37
38 556 decreases in entire profile, slightly below ca. 20%, due to greatly enhanced minerogenic
39
40 557 matter delivery (Figure 3 C, zone KT-L11). It lasts ca. 270 years and was distinguished as a
41
42 558 separate interval in the CONISS analysis of macrofossil data. It contains single macrofossils
43
44 559 of *Betula* sect. *Nanae* and *Betula pubescens*, numerous fruits and urticles of *Carex rostrata*
45
46 560 and the most abundant in the entire profile fruits of *Scirpus sylvaticus*. There is also a single
47
48 561 finding of *Filipendula ulmaria* fruit. Stage KT-6 also corresponds to LMAZ KT-P8,
49
50 562 signaling the more open-space conditions with domination of herbs and shrinkage of
51
52 563 woodlands.
53
54
55
56
57
58
59
60

1
2
3 565 *A part of the stage KT-7 (117.5–106.5 cm, from ca. 10,990 ± 432 to ca. 10,033 ± 707 cal BP,*
4
5 566 *ca. 957 years) Fen with Scirpus sylvaticus (drier conditions) and mineral material delivery*
6
7 567 Stage KT-7 exhibits the lowest sedimentation rate of the whole analysed Kotoń depth section:
8
9 568 0.12 mm year⁻¹ (Figure 2). In this subzone LOI values rise slightly close to 30% due to
10
11 569 organic matter accumulation (sedge-moss fen peat) but still with strong minerogenic
12
13 570 contamination (Figure 3 C, zone KT-L12). Macrofossils of trees, shrubs and dwarf shrubs are
14
15 571 represented by a fruit of *Rubus idaeus*, and higher in the profile also by needles of *Picea abies*
16
17 572 and fruits of *Sambucus racemosa* (Figure 5). Within the investigated part of the stage KT-7
18
19 573 there are abundant fruits of *Scirpus sylvaticus* and some sclerotia of *Cenococcum geophilum*.
20
21 574 The corresponding LPAZ KT-P9 (SM Figure S6) shows substantial vegetation changes: NAP
22
23 575 pollen percentage decreases, whereas several arboreal pollen curves show distinctive increase
24
25 576 in values and continuity: *Pinus sylvestris*-type, *Alnus*, *Picea abies* (confirming the local
26
27 577 presence inferred from plant macrofossils), *Ulmus*, *Corylus avellana* and *Tilia* undiff. These
28
29 578 set of observations indicate the expansion of mixed temperate forest in the warming climate
30
31 579 of the Holocene.
32
33
34
35
36
37
38
39

580

581 **References used in Supplemental Material:**

- 582 Aalto M (1970) Potamogetonaceae fruits I. Recent and subfossil endocarps of the
583 Fennoscandian species. *Acta Botanica Fennica* 88. Helsinki: Societas Pro Fauna Et Flora
584 Fennica: 1–85.
- 585 Anderberg A-L (1994) *Atlas of Seeds and Small Fruits of Northwest-European Plant Species*
586 *with Morphological Descriptions. Part 4. Resedaceae–Umbelliferae*. Stockholm:
587 Swedish Museum of Natural History.
- 588 Berggren G (1969) *Atlas of Seeds and Small Fruits of Northwest-European Plant Species with*
589 *Morphological Descriptions. Part 2: Cyperaceae*. Stockholm: Swedish Natural Science

- 1
2
3 590 Research Council.
4
5
6 591 Berggren G (1981) *Atlas of Seeds and Small Fruits of Northwest-European Plant Species with*
7
8 592 *Morphological Descriptions. Part 3: Salicaceae - Cruciferae*. Stockholm: Swedish
9
10 593 Museum of Natural History.
11
12
13 594 Beug HJ (2004) *Leitfaden Der Pollenbestimmung Für Mitteleuropa Und Angrenzende*
14
15 595 *Gebiete*. München: Verlag Dr. Friedrich Pfeil.
16
17
18 596 Birks HH (2013) Plant macrofossil introduction. In: Elias SA and Mock CJ (eds)
19
20 597 *Encyclopedia of Quaternary Science*. Second Edi. Amsterdam: Elsevier, pp. 593–612.
21
22
23 598 Cappers RTJ, Bekker RM and Jans JEA (2012) *Digital Seed Atlas of the Netherlands/*
24
25 599 *Digitale Zadenatlas van Nederland*. 2nd ed. Groningen: Barkhuis Publishing &
26
27 600 Groningen University Library.
28
29
30 601 Carrión JS, Fernández S, González-Sampériz P, et al. (2009) Quaternary pollen analysis in the
31
32 602 Iberian Peninsula: the value of negative results. *Internet Archaeology* 25:1–53.
33
34
35 603 Climate Data (2024) Stróža i Zawadka. Available at: <https://pl.climate->
36
37 604 [data.org/europa/polska/lesser-poland-voivodeship/stroza-450713/](https://pl.climate-data.org/europa/polska/lesser-poland-voivodeship/stroza-450713/) and <https://pl.climate->
38
39 605 [data.org/europa/polska/lesser-poland-voivodeship/zawadka-450812/](https://pl.climate-data.org/europa/polska/lesser-poland-voivodeship/zawadka-450812/) (accessed 08
40
41 606 August 2024).
42
43
44 607 Erdtman G (1943) *An Introduction to Pollen Analysis*. Waltham, Massachusetts: Chronica
45
46 608 Botanica.
47
48
49 609 Erdtman G (1960) Acetolysis method. A revised description. *Svensk Botanisk Tidskrift* 54:
50
51 610 561–564.
52
53
54 611 Fægri K and Iversen J (1989) *Textbook of Pollen Analysis* (K Fægri, PE Kaland, and K
55
56 612 Krzywinski eds.). 4th ed. Chichester: John Wiley & Sons.

- 1
2
3 613 Feurdean A, Wohlfarth B, Björkman L, et al. (2007) The influence of refugial population on
4
5 614 Lateglacial and early Holocene vegetational changes in Romania. *Review of*
6
7 615 *Palaeobotany and Palynology* 145(3–4): 305–320.
8
9
10 616 GRASS Development Team (2015) Geographic Resources Analysis Support System
11
12 (GRASS) Software, Version 7.0. Open Source Geospatial Foundation. Available at:
13 617
14 <https://grass.osgeo.org> (accessed 05 April 2025).
15 618
16
17
18 619 Hájek M, Horsák M, Hájková P, et al. (2006) Habitat diversity of central European fens in
19
20 620 relation to environmental gradients and an effort to standardise fen terminology in
21
22 621 ecological studies. *Perspectives in Plant Ecology, Evolution and Systematics* 8(2): 97–
23
24 622 114.
25
26
27
28 623 IHE Delft Institute for Water Education (2025) Stream and catchment delineation using
29
30 624 GRASS tools. Education Open CourseWare for GIS. Available at:
31
32 625 <https://courses.gisopencourseware.org/mod/book/view.php?id=53&chapterid=82>
33
34 626 (accessed 06 April 2025).
35
36
37
38 627 Kats NY, Kats SV and Kipiani MG (1965) *Atlas and Keys of Fruits and Seeds Occurring in*
39
40 628 *the Quaternary Deposits of the USSR [in Russian]*. Moscow: Nauka.
41
42
43 629 Körber-Grohne U (1964) Bestimmungsschlüssel für subfossile Juncus- Samen und
44
45 630 Gramineen- Früchte. In: Haarnagel W (ed.) *Probleme Der Küstenforschung Im*
46
47 631 *Südlichen Nordseegebiet 7*. Hildesheim: August Lax, pp. 1–47.
48
49
50
51 632 Körber-Grohne U (1991) Identification key fo subfossil Gramineae fruits. *Probleme der*
52
53 633 *Küstenforschung im Südlichen Nordseegebiet* 18: 169–234.
54
55
56 634 Kowalewski G (2014) *Alogeniczne i Autogeniczne Składowe Zarastania Jezior: Hipoteza*
57
58 635 *Wahań Poziomu Wody*. Poznań: Polskie Towarzystwo Limnologiczne: Bogucki
59
60

- 1
2
3 636 Wydawnictwo Naukowe.
4
5
6 637 Margielewski W (2001a) Late Glacial and Holocene climatic changes registered in forms and
7
8 638 deposits of the Klaklowo landslide (Beskid Średni Range, Outer Carpathians). *Studia*
9
10 639 *Geomorphologica Carpatho-Balcanica* 35(2001): 63–79.
11
12
13 640 Margielewski W (2001b) Rejestr zmian klimatycznych późnego glacialu i holocenu w obrębie
14
15 641 torfowiska pod Kotoniem (Beskid Średni, Karpaty Zewnętrzne). *Przegląd Geologiczny*
16
17 642 49(12): 1161–1166.
18
19
20
21 643 Margielewski W, Obidowicz A and Pelc S (2003) Late Glacial-Holocene peat bog on Kotoń
22
23 644 Mt. and its significance for reconstruction of palaeoenvironment in the Western Outer
24
25 645 Carpathians (Beskid Makowski Range, South Poland). *Folia Quaternaria* 74: 35–56.
26
27
28
29 646 Mauquoy D and van Geel B (2007) Mire and peat macros. In: Elias SA (ed.) *Encyclopedia of*
30
31 647 *Quaternary Science, Volume 3*. 2nd ed. Amsterdam: Elsevier Science, pp. 2315–2336.
32
33
34 648 Mirek Z (2013) Altitudinal vegetation belts of the Western Carpathians. In: Obidowicz A,
35
36 649 Madeyska E, and Turner C (eds) *Postglacial History of Vegetation in the Polish Part of*
37
38 650 *the Western Carpathians Based on Isopollen Maps*. Kraków: W. Szafer Institute of
39
40 651 Botany, Polish Academy of Sciences, pp. 15–21.
41
42
43
44 652 Moore PD, Webb JA and Collinson ME (1991) *Pollen Analysis*. Oxford: Blackwell Scientific
45
46 653 Publications.
47
48
49 654 Pilch J, Margielewski W, Stachowicz-Rybka R and Buczek K (2025a) The Bølling-Older
50
51 655 Dryas-Allerød transition (ca. 14,600–13,500 cal BP) in the palaeoecological record of
52
53 656 the Kotoń landslide fen (the Outer Western Carpathians, S Poland) – from the local to
54
55 657 extraregional perspective. *Radiocarbon* (in press).
56
57
58
59 658 Pilch J, Margielewski W, Stachowicz-Rybka R, Buczek K, et al. (2025b) Characeae-
60

- 1
2
3 659 dominated vegetation succession as a key to understanding the late glacial environmental
4
5 660 changes (ca. 14,600–13,500 cal yrs BP): a multi-proxy record of palaeo-waterbody
6
7 661 developed within the Klaklowo landslide, the Outer Western Carpathians, S Poland.
8
9
10 662 *Journal of Paleolimnology* 73(3): 195–215.
11
12
13 663 QGIS Development Team (2021) QGIS Geographic Information System. Open Source
14
15 664 Geospatial Foundation Project, Version 3.22.10. Available at: <http://qgis.org> (accessed
16
17 665 12 December 2022).
18
19
20 666 Rasmussen SO, Bigler M, Blockley SP, et al. (2014) A stratigraphic framework for abrupt
21
22 667 climatic changes during the Last Glacial period based on three synchronized Greenland
23
24 668 ice-core records: Refining and extending the INTIMATE event stratigraphy. *Quaternary*
25
26 669 *Science Reviews* 106: 14–28.
27
28
29
30 670 Reille M (1992) *Pollen et Spores d'Europe et d'Afrique Du Nord*. Marseille: Laboratoire de
31
32 671 Botanique Historique et Palynologie.
33
34
35 672 Van Geel B (1978) A palaeoecological study of Holocene peat bog section in Germany and
36
37 673 The Netherlands, based on the analysis of pollen, spores and macro- and microscopic
38
39 674 remains of fungi, algae, coprophytes and animals. *Review of Palaeobotany and*
40
41 675 *Palynology* 25(1): 1–120.
42
43
44
45 676 Van Geel B, Bohnecke SJP and Dee H (1980) A palaeoecological study of an upper Late
46
47 677 Glacial and Holocene sequence from “De Borchert”, The Netherlands. *Review of*
48
49 678 *Palaeobotany and Palynology* 31: 367–448.
50
51
52
53 679 Van Geel B, Buurman J, Brinkkemper O, et al. (2003) Environmental reconstruction of a
54
55 680 Roman Period settlement site in Uitgeest (The Netherlands), with special reference to
56
57 681 coprophilous fungi. *Journal of Archaeological Science* 30(7): 873–883.
58
59
60

- 1
2
3 682 Van Geel B, Zazula GD and Schweger CE (2007) Spores of coprophilous fungi from under
4
5 683 the Dawson tephra (25 300 14C years BP), Yukon Territory, northwestern Canada.
6
7 684 *Palaeogeography, Palaeoclimatology, Palaeoecology* 252: 481–485.
8
9
10 685 Velichkevich F and Zastawniak E (2006) *Atlas of the Pleistocene Vascular Plant*
11
12 686 *Macrofossils of Central and Eastern Europe. Part 1: Pteridophytes and*
13
14 687 *Monocotyledons*. Kraków: W. Szafer Institute of Botany, Polish Academy of Sciences.
15
16
17
18 688 Velichkevich F and Zastawniak E (2008) *Atlas of the Pleistocene Vascular Plant*
19
20 689 *Macrofossils of Central and Eastern Europe. Part 2: Herbaceous Dicotyledones.*
21
22
23 690 Kraków: W. Szafer Institute of Botany, Polish Academy of Sciences.
24
25
26 691
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46

692 **Table S9.** Distinguishable similarities and differences recognized in the vegetation and lithological records of the Kotoń and Klaklowo landslide
693 fens.

Record of vegetation/habitat changes	Lithological record (minerogenic sediment delivery)
<p>Similarities:</p> <p>Asynchronous:</p> <p>1: Ca. 13,610 cal BP (with the onset of the GI-1c2 phase) - local habitats become unified in both sites as a long-lasting fens (ca. 13,900 ± 56 cal BP – the long-lasting fen stage was reached in Kotoń, ca. 13,610 cal BP – long-lasting fen stage was reached in Klaklowo).</p> <p>2 Local establishment of <i>Betula</i> woodlands: first at the Kotoń site, ca. 13,810 ± 70 cal BP, and subsequently in the the Klaklowo site, ca. 13,710 ± 53 cal BP.</p> <p>3 During GI-1a–c/Allerød, GS-1/Younger Dryas and at the beginning of the Preboreal – the similar (but asynchronous) habitats succession (first the less wet 5a, later waterlogging of the lower part of the stage 5b and again less wet upper part of the stage 5b).</p> <p>4 At the onset of the supposed Preboreal/Boreal period (ca. 10,990 ± 432 for Kotoń and ca. 11,120 ± 99 cal BP for Klaklowo) corresponding composition of macrofossils (<i>Scirpus sylvaticus</i>,</p>	<p>Similarities:</p> <p>1 The beginning of the Holocene is manifested by a gradual intensification of the supply of minerogenic material to the Kotoń (since ca. 11,720 ± 123 cal BP) and Klaklowo (ca. 11,720 ± 178 cal BP).</p> <p>2 The supposed Preboreal/Boreal period - the lowest sedimentation rate of the whole profiles was determined, 0.12 mm year⁻¹ for Kotoń and ca. 0.10 mm year⁻¹ for Klaklowo deposits (in both cases minerogenic-organic deposits).</p>

<p><i>Cenococcum geophilum</i>) and pollen (<i>Picea abies</i>, <i>Ulmus</i>, <i>Alnus</i> etc.), temperate mixed forests expansion.</p>	
<p>Synchronous:</p> <p>1 The local presence/establishment of pine woodlands (ca. 13,650 ± 103 cal BP in the Kotoń site and ca. 13,630 ± 43 in the Klaklowo site).</p> <p>2 Toward the end of Allerød/beginning of Younger Dryas, the trend of increasing/dominating of <i>Pinus</i> pollen/macrofossils, expansion of pine forest.</p> <p>3 GI-1c1/Allerød - since around 13,450 cal BP the tree birch recession (pollen, macrofossils) at both sites.</p> <p>4 During the GS-1/Younger Dryas - the maximum percentage of <i>Pinus sylvestris</i>-type pollen of the entire pollen sequences was registered in both Kotoń (KT-P6-<i>Pinus</i>) and Klaklowo (KK-P7-<i>Pinus</i>-NAP) sites. <i>Pinus sylvestris</i> macrofossils also numerous.</p> <p>5 At the beginning of the Holocene - an ultimate almost synchronous decline of Bryopsida at a time of 11,510 ± 161 in Kotoń and 11,560 ± 177 in Klaklowo.</p>	
<p>Differences</p>	<p>Differences</p>
<p>1</p>	<p>1</p>

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46

GI-1a–c/Allerød - First appearance ($>14,630 \pm 349$ cal BP) and expansion ($13,540 \pm 28$ cal BP) of *Larix decidua* macrofossils in Klaklowo. In Kotoń much later: GS-1/Younger Dryas cooling - trace occurrences of *Larix decidua* in Kotoń site can be dated to ca. $12,560 \pm 198$, increased abundance of *Larix decidua* macrofossils around $11,850 \pm 82$.

2
GS-1/Younger Dryas cooling – weak NAP/*Artemisia* pollen signal only in the Klaklowo landslide fen.

3
The beginning of the Holocene/Preboreal period - decline of *Pinus sylvestris* ($11,670 \pm 142$ cal BP), Coniferae ($11,610 \pm 160$) and *Larix decidua* ($11,460 \pm 208$ cal BP) in Kotoń, earlier than in Klaklowo.

4
Preboreal period/Preboreal oscillation (KT-P8: NAP-*Betula-Pinus*) - increase in NAP/*Artemisia* pollen visible only in the Kotoń fen.

5
Onset of the Preboreal oscillation – in Klaklowo temporal recession of *Pinus sylvestris* and *Larix decidua* ($11,260 \pm 263$ cal BP).

6
Ending of the Preboreal oscillation – in Klaklowo an ultimate recession of all *Carex* species ($11,140 \pm 88$ cal BP), an almost total disappearance of *Pinus sylvestris* and a total decline of *Larix*

GI-1c1/ Allerød - A thin minerogenic intercalation devoid of pollen (ca. $13,490 \pm 25$ cal BP) in Klaklowo record, not registered in Kotoń.

2
A cold climatic GI-1b/Gerzensee oscillation reflected only in LOI (ca. $13,170 \pm 81$) and pollen data of the Klaklowo site (ca. $13,140 \pm 79$ cal BP).

3
Cold Preboreal oscillation expressed in abrupt and huge minerogenic input in the Kotoń fen (from ca. $11,260 \pm 263$ to ca. $10,990 \pm 432$ cal BP, ca. 270 years) - only 7.5 cm thickness of minerogenic layer, and in Klaklowo (ca. $11,240 \pm 92$ to ca. $11,120 \pm 99$ cal BP, ca. 120 years) ca. 47.5 cm thickness of minerogenic layer (very high sedimentation rate: $4.20 \text{ mm year}^{-1}$).

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46

694

<i>decidua</i> and <i>Betula</i> sect. <i>Albae</i> (all three taxa disappearances are dated to ca. 11,120 ± 99 cal BP).	
--	--

For Peer Review

14.4. Publikacja 2 – Tytuł

Pilch, J., Margielewski, W., Stachowicz-Rybka, R., Buczek, K., Stolarczyk, M., Musielok, Ł., Korzeń, K., Sala, D., 2025. Characeae-dominated vegetation succession as a key to understanding the late glacial environmental changes (ca. 14,600–13,500 cal yrs BP): a multi-proxy record of palaeo-waterbody developed within the Klaklowo landslide, the Outer Western Carpathians, S Poland. *Journal of Paleolimnology* 73, 195–215. <https://doi.org/10.1007/s10933-025-00355-1>

MNISW (2024 rok): 100 pkt.

IF: (5-letni) 1,7; (2024 rok) 1,3

14.5. Publikacja 2 – Oświadczenia współautorów

Kraków, 20.10.2025

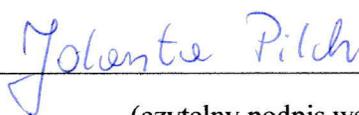
Mgr inż. Jolanta Pilch
Instytut Ochrony Przyrody
Polskiej Akademii Nauk
al. Adama Mickiewicza 33,
31-120 Kraków

OŚWIADCZENIE

Oświadczam, że w pracy:

Pilch, J., Margielewski, W., Stachowicz-Rybka, R., Buczek, K., Stolarczyk, M., Musielok, Ł., Korzeń, K., Sala, D., 2025. Characeae-dominated vegetation succession as a key to understanding the late glacial environmental changes (ca. 14,600–13,500 cal yrs BP): a multi-proxy record of palaeo-waterbody developed within the Klakłowo landslide, the Outer Western Carpathians, S Poland. *J. Paleolimnol.* 73, 195–215. <https://doi.org/10.1007/s10933-025-00355-1>

mój udział polegał na: wykonaniu prac w terenie, poborze próbek, analizie makroszczątków roślin, opracowaniu (statystycznym i graficznym) danych: makroszczątkowych, uziarnienia, palinologicznych, geochemicznych, datowań radiowęglowych (w tym przygotowywanie modelu wiek-głębokość), przeprowadzeniu interpretacji paleośrodowiska oraz przygotowanie manuskryptu (draft oraz recenzja i redagowanie). Mój udział w pracach wynosi 90%.



(czytelny podpis współautora)

Kraków, 20.10.2025

Dr hab. inż Włodzimierz Margielewski, prof. IOP PAN
Instytut Ochrony Przyrody
Polskiej Akademii Nauk
al. Adama Mickiewicza 33,
31-120 Kraków

O Ś W I A D C Z E N I E

Oświadczam, że w pracy:

Pilch, J., **Margielewski, W.**, Stachowicz-Rybka, R., Buczek, K., Stolarczyk, M., Musielok, Ł., Korzeń, K., Sala, D., 2025. Characeae-dominated vegetation succession as a key to understanding the late glacial environmental changes (ca. 14,600–13,500 cal yrs BP): a multi-proxy record of palaeo-waterbody developed within the Klakłowo landslide, the Outer Western Carpathians, S Poland. *J. Paleolimnol.* 73, 195–215. <https://doi.org/10.1007/s10933-025-00355-1>

mój udział polegał na: pomocy w wykonaniu prac w terenie, konceptualizacji, nadzorze, pomocy w interpretacji paleośrodowiskowej i przygotowaniu manuskryptu (recenzja i redagowanie). Mój udział w pracach wynosi 2,5%.



(czytelny podpis współautora)

Kraków, 20.10.2025

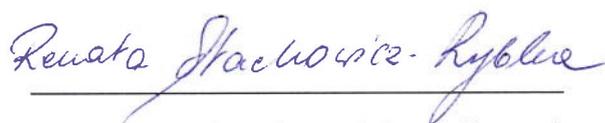
Dr hab. Renata Stachowicz Rybka, prof. IB PAN
Instytut Botaniki im. W. Szafera
Polskiej Akademii Nauk
ul. Lubicz 46,
31-512 Kraków

O Ś W I A D C Z E N I E

Oświadczam, że w pracy:

Pilch, J., Margielewski, W., **Stachowicz-Rybka, R.**, Buczek, K., Stolarczyk, M., Musielok, Ł., Korzeń, K., Sala, D., 2025. Characeae-dominated vegetation succession as a key to understanding the late glacial environmental changes (ca. 14,600–13,500 cal yrs BP): a multi-proxy record of palaeo-waterbody developed within the Klakłowo landslide, the Outer Western Carpathians, S Poland. *J. Paleolimnol.* 73, 195–215. <https://doi.org/10.1007/s10933-025-00355-1>

mój udział polegał na: pomocy w przeprowadzeniu analizy makroszczałków roślin, konceptualizacji, nadzorze, pomocy w interpretacji paleośrodowiskowej i przygotowaniu manuskryptu (recenzja i redagowanie). Mój udział w pracach wynosi 2,5%.



(czytelny podpis współautora)

Kraków, 20.10.2025

Dr Krzysztof Buczek
Instytut Ochrony Przyrody
Polskiej Akademii Nauk
al. Adama Mickiewicza 33,
31-120 Kraków

O Ś W I A D C Z E N I E

Oświadczam, że w pracy:

Pilch, J., Margielewski, W., Stachowicz-Rybka, R., **Buczek, K.**, Stolareczyk, M., Musielok, Ł., Korzeń, K., Sala, D., 2025. Characeae-dominated vegetation succession as a key to understanding the late glacial environmental changes (ca. 14,600–13,500 cal yrs BP): a multi-proxy record of palaeo-waterbody developed within the Klaklowo landslide, the Outer Western Carpathians, S Poland. *J. Paleolimnol.* 73, 195–215. <https://doi.org/10.1007/s10933-025-00355-1>

mój udział polegał na: pomocy w wykonaniu prac w terenie, konceptualizacji, pomocy w interpretacji paleośrodowiskowej, opracowaniu modelu wiek-głębokość oraz przygotowaniu manuskryptu (recenzja i redagowanie). Mój udział w pracach wynosi 1%.



(czytelny podpis współautora)

Kraków, 20.10.2025

Dr Mateusz Stolarczyk
Instytut Geografii i Gospodarki Przestrzennej
Uniwersytet Jagielloński
ul. Gronostajowa 7,
30-387 Kraków

OŚWIADCZENIE

Oświadczam, że w pracy:

Pilch, J., Margielewski, W., Stachowicz-Rybka, R., Buczek, K., **Stolarczyk, M.**, Musielok, Ł., Korzeń, K., Sala, D., 2025. Characeae-dominated vegetation succession as a key to understanding the late glacial environmental changes (ca. 14,600–13,500 cal yrs BP): a multi-proxy record of palaeo-waterbody developed within the Klakłowo landslide, the Outer Western Carpathians, S Poland. *J. Paleolimnol.* 73, 195–215. <https://doi.org/10.1007/s10933-025-00355-1>

mój udział polegał na: wykonaniu analizy geochemicznej i uziarnienia oraz pomocy w przygotowaniu manuskryptu (recenzja i redagowanie). Mój udział w pracach wynosi 1%.



(czytelny podpis współautora)

Kraków, 20.10.2025

Dr Łukasz Musielok
Instytut Geografii i Gospodarki Przestrzennej
Uniwersytet Jagielloński
ul. Gronostajowa 7,
30-387 Kraków

OŚWIADCZENIE

Oświadczam, że w pracy:

Pilch, J., Margielewski, W., Stachowicz-Rybka, R., Buczek, K., Stolarczyk, M., **Musielok, Ł.**, Korzeń, K., Sala, D., 2025. Characeae-dominated vegetation succession as a key to understanding the late glacial environmental changes (ca. 14,600–13,500 cal yrs BP): a multi-proxy record of palaeo-waterbody developed within the Klaklowo landslide, the Outer Western Carpathians, S Poland. *J. Paleolimnol.* 73, 195–215. <https://doi.org/10.1007/s10933-025-00355-1>

mój udział polegał na: wykonaniu analizy geochemicznej i uziarnienia oraz pomocy w przygotowaniu manuskryptu (recenzja i redagowanie). Mój udział w pracach wynosi 1%.



(czytelny podpis współautora)

Kraków, 20.10.2025

Dr inż. Dariusz Sala
Instytut Fizyki Jądrowej
Polskiej Akademii Nauk
ul. Radzikowskiego 152
31-342 Kraków

OŚWIADCZENIE

Oświadczam, że w pracy:

Pilch, J., Margielewski, W., Stachowicz-Rybka, R., Buczek, K., Stolarczyk, M., Musielok, Ł., Korzeń, K., **Sala, D.**, 2025. Characeae-dominated vegetation succession as a key to understanding the late glacial environmental changes (ca. 14,600–13,500 cal yrs BP): a multi-proxy record of palaeo-waterbody developed within the Klakłowo landslide, the Outer Western Carpathians, S Poland. *J. Paleolimnol.* 73, 195–215. <https://doi.org/10.1007/s10933-025-00355-1>

mój udział polegał na: wykonaniu analizy geochemicznej. Mój udział w pracach wynosi 1%.



(czytelny podpis współautora)

Kraków, 20.10.2025

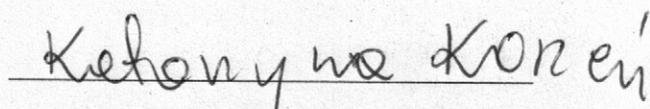
Dr Katarzyna Korzeń
ul. Kazimierza Wielkiego 110/3-4,
30-082 Kraków

OŚWIADCZENIE

Oświadczam, że w pracy:

Pilch, J., Margielewski, W., Stachowicz-Rybka, R., Buczek, K., Stolarczyk, M., Musielok, Ł., **Korzeń, K.**, Sala, D., 2025. Characeae-dominated vegetation succession as a key to understanding the late glacial environmental changes (ca. 14,600–13,500 cal yrs BP): a multi-proxy record of palaeo-waterbody developed within the Klakłowo landslide, the Outer Western Carpathians, S Poland. *J. Paleolimnol.* 73, 195–215. <https://doi.org/10.1007/s10933-025-00355-1>

mój udział polegał na: wykonaniu analizy palinologicznej i palinomorf niepyłkowych (NPPs). Mój udział w pracach wynosi 1%.


(czytelny podpis współautora)

14.6. Publikacja 2



Characeae-dominated vegetation succession as a key to understanding the late glacial environmental changes (ca. 14,600–13,500 cal yrs BP): a multi-proxy record of palaeo-waterbody developed within the Klakłowo landslide, the Outer Western Carpathians, S Poland

Jolanta Pilch · Włodzimierz Margielewski · Renata Stachowicz-Rybka ·
Krzysztof Buczek · Mateusz Stolarczyk · Łukasz Musielok ·
Katarzyna Korzeń · Dariusz Sala

Received: 20 July 2024 / Accepted: 17 February 2025 / Published online: 9 April 2025
© The Author(s) 2025, corrected publication 2025

Abstract Aquatic ecosystems developed within landslide depressions are common in the region of the Outer Western Carpathi, and they frequently record detailed pond-to-fen vegetation successions initiated by the warming climate of the Bølling-Allerød period. In the Klakłowo landslide fen (the Beskid Makowski Mountains, S Poland) the late glacial deposits are represented by a long (approximately 2.5 m) minerogenic-organic sequence with a distinct section corresponding to the Older Dryas cooling. Here, we applied a high-resolution multi-proxy study (grain size, geochemical, pollen and macrofossil analyses, radiocarbon dating), and we reconstructed vegetation,

hydrological and climate changes recorded in the bottom part of the Klakłowo fen sequence (depth range of 250–367 cm). A special emphasis was put on investigating the conditions affecting development of Characeae-dominated vegetation succession and possible reasons behind the discontinuous pollen record. Multi-proxy results revealed that the late glacial sequence (ca. 14,600–13,500 mod. cal yrs BP) of the Klakłowo fen consisted of five palaeoecological stages of development which correspond to the Greenland ice core and Gerzensee chronologies. During the first stage, presumably dry and cold conditions of steppe-tundra prevailed in the surroundings of a poor-in-vegetation Klakłowo waterbody I, matching the Oldest Dryas and Bølling climatic phases. Deterioration of the pollen record observed within this stage

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10933-025-00355-1>.

J. Pilch (✉) · W. Margielewski · K. Buczek
Institute of Nature Conservation, Polish Academy
of Sciences, Al. Adama Mickiewicza 33, 31-120 Kraków,
Poland
e-mail: pilch@iop.krakow.pl

W. Margielewski
e-mail: margielewski@iop.krakow.pl

K. Buczek
e-mail: buczek@iop.krakow.pl

R. Stachowicz-Rybka
W. Szafer Institute of Botany, Polish Academy of Sciences,
Lubicz 46, 31-512 Kraków, Poland
e-mail: r.stachowicz@botany.pl

M. Stolarczyk · Ł. Musielok
Institute of Geography and Spatial Management,
Jagiellonian University, Gronostajowa 7, 30-387 Kraków,
Poland
e-mail: mateusz.stolarczyk@uj.edu.pl

Ł. Musielok
e-mail: l.musielok@uj.edu.pl

K. Korzeń
Kraków, Poland

D. Sala
Institute of Nuclear Physics, Polish Academy of Sciences,
Radzikowskiego 152, 31-342 Kraków, Poland
e-mail: dariusz.sala@ifj.edu.pl

most probably resulted from the post-depositional oxidation due to periodical water-level changes of the waterbody I. During the second stage, palaeo-pond was transformed into a short-lasting fen likely with a more wide-spread steppe-tundra vegetation in the catchment area reflecting the dry and cold climate of the Older Dryas. Further two sub-stages of the Klaklowo waterbody II were characterized by aquatic vegetation and boreal forest succession signaling the Allerød warming. The co-occurrence of macrophytes dominated by wide-spread Characeae meadows and intense precipitation of calcium carbonate indicate that alkaline conditions prevailed in the Klaklowo waterbody II at that time. Carbonate formation probably resulted from leaching of carbonate-bearing bedrock in the catchment area and calcium-rich groundwater supply to the pond intensified by increased precipitation. The last stage is characterized by the disappearance of Characeae meadows which may be attributed to multiple factors including the transition of the palaeo-pond into a fen and related acidification.

Keywords Landslide fen · Macrofossil analysis · Discontinuous pollen record · Bølling · Older Dryas · Allerød

Introduction

For the late glacial period, Bølling and Allerød climate warmings were separated by a short (ca. 100–200 years) climate cooling called Older Dryas that is observed within the climate-biostratigraphic division for Scandinavia (Iversen 1954). Among deposits of peatlands and lakes from various hypsometrical settings, the Bølling-Older Dryas-Allerød sequence is often distinctively expressed in palaeo-records of mountainous sites due to the possible proximity of vegetation ecotones and favourable local environmental features, e.g. altitude, exposure, topography and hydrology (Feurdean et al. 2007; Ammann et al. 2013; Margielewski et al. 2022a). Previous research conducted in the Outer Western Carpathians has proven that landslide fens, small peatlands developed within landslide depressions, are sensitive indicators of palaeoenvironmental and palaeoclimatic changes (Margielewski 2018). In the Klaklowo landslide

fen, as well as in the neighbouring Kotoń landslide fen (Beskid Makowski Mountains, Outer Western Carpathians, S Poland), multi-proxy analysis of the fen deposits revealed a long (ca. 2.5 m and 3.5 m, respectively) minerogenic-organic sequence of the late glacial (Margielewski 2001; Margielewski et al. 2003). Based on the plant-macrofossil analysis previously conducted for the Kotoń site, lacustrine clastic deposits of the Bølling Interstadial showed some evidence of a warmer climate only within a thin organic horizon with seeds of *Viola palustris* (Margielewski et al. 2003). During the Older Dryas cooling the Kotoń waterbody was shallow and eutrophic, surrounded by reeds and inhabited by *Chara* sp. and other macrophytes (Margielewski et al. 2003). With the onset of Allerød warming, the share of sedges increased and became dominant, in this way causing overgrowing of the palaeo-waterbody by vegetation (Margielewski et al. 2003). As a result, the Bølling-Older Dryas-Allerød climatic oscillations were well-documented by the local aquatic and boggy plant succession of the Kotoń landslide fen.

In modern freshwater ecosystems, which constitute analogues to ancient lakes and peatlands, the dynamics of Characeae macroalgae and other macrophytes have been thoroughly studied from the perspective of the ongoing climate change (Hargeby et al. 2004; Rip et al. 2007; Sleith et al. 2018). Growth and stability of Characeae phytocenosis depends on many environmental factors: low turbidity of water, favourable depth of waterbody, oligo- to mesotrophic conditions, basic pH and buffering capacity of water, temperature (including interannual changes influencing the length of a spring clear-water phase), salinity and others (Kufel and Kufel 2002; Hargeby et al. 2004; Pełechaty et al. 2013; Choudhury et al. 2019). These in-situ factors are, in turn, modified by different external drivers, mostly related to characteristics of the lake catchment (e.g. nutrient and solid material delivery) and climate (Hargeby et al. 2004).

Water-level fluctuations in palaeo-lakes and mires were frequently triggered by climate changes, thus, they may be effectively correlated with changes in the pollen sequences (Słowiński et al. 2016; Margielewski et al. 2022b, 2024). Water-table lowering may also, however, result in aerobic conditions, which in turn can cause

the decomposition of pollen grains. Deteriorated pollen records, either in a form of entirely sterile or partially depleted sequences (sterile horizons), frequently hamper a detailed reconstruction of past vegetation (Carrión et al. 2007, 2009). Among 221 study sites in the Iberian Peninsula investigated in terms of discontinuous pollen records, 36 localities concerned lakes/palaeolakes and peat bogs (Carrión et al. 2009). On the other hand, discontinuous pollen records and other proxies may indicate prolonged exposure to subaerial conditions. For instance, as iron oxidizes faster than manganese, low Fe/Mn ratios determined by geochemical analysis indicate good oxygenation of bottom water and can be used for palaeo-reconstructions of redox conditions (Naeyer et al. 2013). Furthermore, geochemical indicators usually used in soil research can be applied: high levels of oxygenation cause mineralization of ammonium nitrogen to nitrate nitrogen, resulting in NO_3/NH_4 ratios higher than 1 (Gotkiewicz 1973, 1996). Additionally, water-table fluctuations can be indirectly interpreted from changing contents of soil organic carbon (SOC) and total nitrogen (TN), as well as SOC/TN ratios. These parameters allow for determining increased biomass input and terrestrial vs aquatic sources of organic matter in lacustrine/peatland sediments (Zeng et al. 2017).

Here, we present results of a new multi-proxy study of recently collected sediment cores from the Klakłowo landslide fen, including grain size, geochemical (SOC, TN, N-NH_4 , N-NO_3 , P-PO_4 , CaCO_3 , and selected results of ICP-MS analysis: Mn and Fe), palynological and non-pollen palynomorphs, and—particularly—plant macrofossil analyses with the addition of determinable taxa of animal remains (e.g. Ostracoda, Porifera, Chironomidae), and radiocarbon dating. The main research objective was to reconstruct past vegetation, climate and hydrological changes recorded in the bottom part of the late glacial sedimentary sequence (depth section of 250–367 cm; Bølling, Older Dryas and the beginning of Allerød). A special attention was paid to the development of a well-pronounced Characeae-dominated aquatic plant succession revealed—similarly to the neighbouring Kotoń site—by plant-macrofossil analysis in the supposed Older Dryas deposits. Furthermore,

the possible reasons behind the discontinuous pollen record were investigated for the Klakłowo fen deposits.

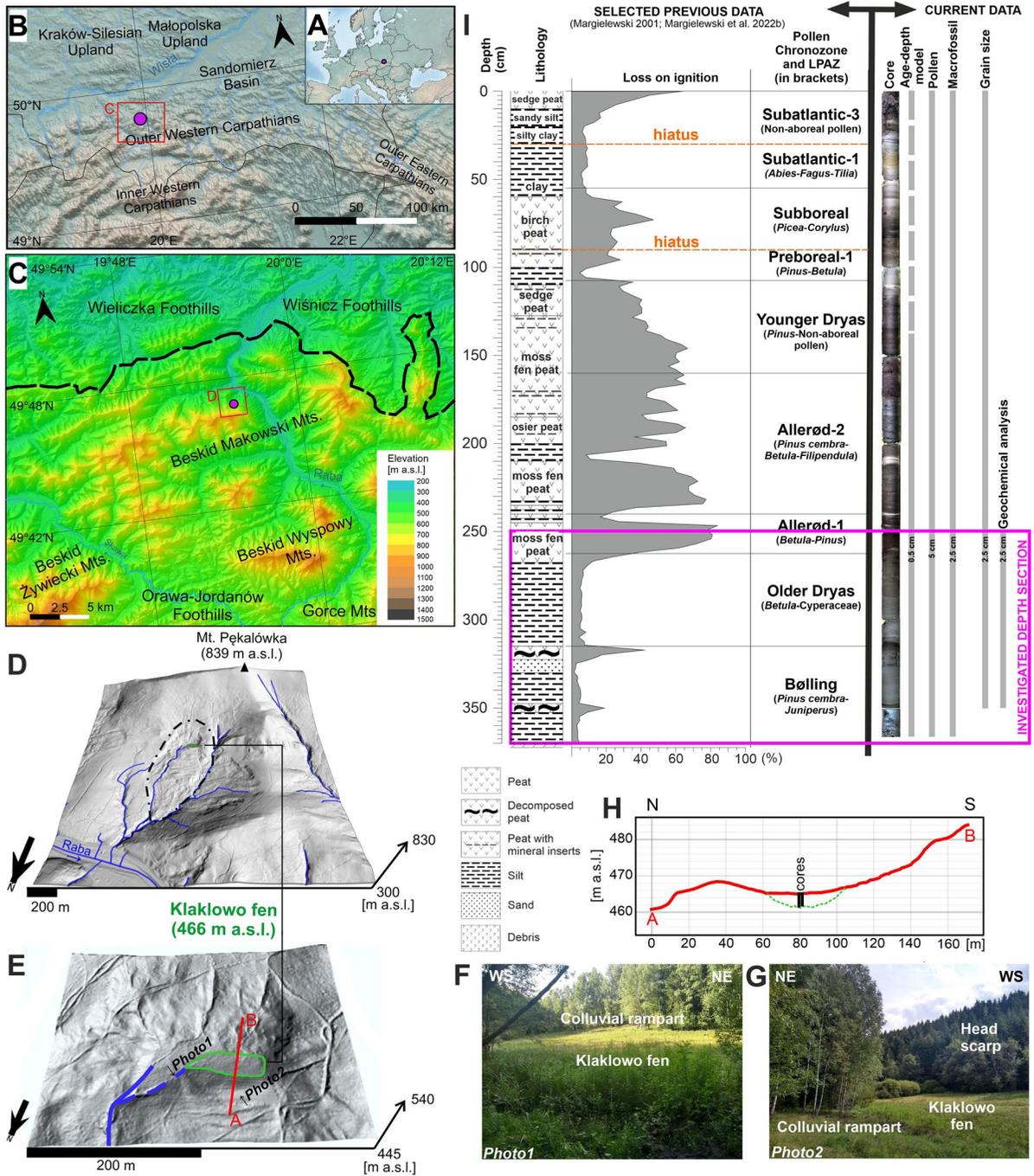
Site description

Geological and geomorphological setting

The study site is located in the Beskid Makowski Mountains, which is part of the Outer Western Carpathians in the south of Poland (Fig. 1 A and B). Geologically, it is situated within the Siary Subunit of the Magura Unit (Książkiewicz et al. 2016), which is one of the overthrust tectonic units (nappes) that form the Outer Western Carpathians. The Carpathian orogen is built of flysch rocks comprising siliciclastic-clayey turbidites (occasionally also of carbonate and siliceous rocks) of the age ranging from Late Jurassic to Early Miocene (Książkiewicz 1972). The investigated Klakłowo landslide (centre at 450 m a.s.l.) and the subsequently formed peatland is embedded in the northern slope of Mt. Pękałówka (839 m a.s.l.), opening toward the valley of one of the Raba River tributaries (Fig. 1 D). Details on the landslide geometry and geological description are given in the Electronic Supplementary Material (ESM). The depression of the Klakłowo fen is elongated latitudinally (about 100 m long), shorter longitudinally (40 m wide) with a shape that is slightly bent southward due to the semicircular head scarp of the landslide (70 m high) encompassing it from the south (Fig. 1 E–H). From the north the depression is dammed with colluvial rampart, on the right of which a stream is flowing out from the fen into the valley (Fig. 1 E–H). At present, the Klakłowo landslide's sub-scarp depression is a mire of minerogenic type (a fen) (Fig. 1 F and G).

Climate, hydrology and vegetation

The mean annual precipitation for the Beskid Makowski Mountains is 800–1000 mm and mean annual temperature ranges from 8.0 to 8.5 °C (Tomczyk and Bednorz 2022). With respect to surface waters, there are small watercourses (some of them periodical) flowing down from the head scarp, mixing within the basin of the fen and flowing out as one stream along the eastern boundary of the landslide (Fig. 1 E). Regional and local topography, climate and hydrology influence the vegetation patterns



◀**Fig. 1** Location of the Klaklowo landslide fen (purple circle) in Europe (A), the region of the Outer Western Carpathian (B) and the Beskid Makowski Mountains (C), dashed line in part C—boundary between foothills and Beskids' relief zones; D Klaklowo landslide zone (outlined with the dashed line) with the position of the Klaklowo landslide fen (area in green), E present-day area (green solid line) of the fen with A-B cross-section (see H); F and G present-day Klaklowo fen (photo by Jolanta Pilch); H A, B cross-section through fen (see E) with the position of the cores collected for the purpose of the current study; I on the left—selected results from the previous study of the Klaklowo landslide fen (Margielewski 2001; Margielewski et al. 2022b): lithology/peat type description, loss on ignition curve, chronozones and local pollen assemblages zones (LPAZ) (by V. Zernitskaya); on the right—new analyses carried out in the present study—length of a grey bar shows the extent of the analysis along the core, dashed bar—sections with analysis in progress; investigated depth section—section of the deposits presented in this paper. Sources of basemaps used in Fig. 1 are given in ESM

(Fig. 1 F and G): nowadays the slopes of the Beskid Makowski Mountains are located within submontane (< 550 m a.s.l.) and the lower montane vegetation belt (550–870 m a.s.l.) and are overgrown mainly with mixed forest with predominance of beech (*Fagus sylvatica*) and fir (*Abies alba*) and some occurrence of spruce (*Picea* sp.). Birch (*Betula* sp.) appears locally on the landslide surfaces and it is also present in the Klaklowo fen vicinity. Willow (*Salix* sp.) shrubs are present at the swampy sites, whereas wet margins of streams are covered by alder (*Alnus* sp.) (Mirek 2013).

Materials and methods

Coring and sampling

Sediment cores were collected from the central (deepest) part of the Klaklowo fen depression (N 49° 46.772'; E 19° 55.383'; 466 m a.s.l.; Fig. 1 H) using INSTORF Russian peat sampler (diameter: 8 cm). The drilling site was repeated at the same location which was probed during an earlier study (Margielewski 2001) to enable comparison between the profiles. Bedrock of the fen was reached at the maximum depth of 367 cm (Fig. 1 H and I). Subsequently, cores were sampled for multi-proxy analyses: pollen and NPPs, plant macrofossils, radiocarbon dating, grain size and geochemistry (Fig. 1 I). To investigate the

targeted late glacial climatic oscillations, the depth section of 250–367 cm was selected as the primary area of subsampling. Sampling interval was 2.5 cm except for the pollen analysis in which it was 5 cm (Fig. 1). However, the sampling interval was modified at some depth points of the profile according to requirements of a given analysis (e.g. excluding samples made of pure organics in granulometric analysis), what resulted in a slightly changing number of samples per proxy. All maps, 3D views and cross-sections presenting localization of the study area and drilling site (Fig. 1) were compiled in QGIS 3.10.8.

Radiocarbon dating and age-depth model

In total, ten radiocarbon dates were obtained from a depth section of 140–367 cm of the sediment core at sampling spots corresponding to stratigraphic boundaries or significant changes in lithology (Table 1). Organic material (mostly plant fruits and aerial parts of moss stems) was selected during macrofossil analysis for Acceleration Mass Spectrometry (AMS) dating. Obtained ¹⁴C age data were further calibrated using the OxCal v. 4.4 software (Bronk Ramsey 2009) and the IntCal20 calibration curve (Reimer et al. 2020) (Table 1). The chronology of the Klaklowo sediment sequence was derived by constructing the Bayesian age-depth model based on eight ¹⁴C AMS dates. Two dates, MKL–A5610 and MKL–A5462, which constituted the two first attempts of dating the beginning of the accumulation of the peat sequence at a depth of approx. 260–270 cm, were excluded from the calculations due to their distinctively overestimated ages. The modelling of the age-depth curve was performed in the OxCal software using the P_sequence function, interpolation=2 (0.5 cm), parameters k0=1 and log10(k/k0)=U(-1,1), and by applying the IntCal 20 calibration curve. The modelled age (μ values rounded to tens) expressed as mod. cal yrs BP and sedimentation rate expressed in mm year⁻¹ were determined for the sediment sequence.

Grain-size analysis

The grain-size analysis was carried out using laser diffraction with the Mastersizer 3000 granulometer (Malvern Panalytical, United Kingdom). Content

Table 1 Results of radiocarbon dating of the Klaklwo landslide fen deposits

No	Depth (cm)	Material	Macrofossil type	Lab code*	Age ¹⁴ C (yrs BP)	Calibrated age 2σ 95.4% (cal yrs BP)	Mean μ (cal yrs BP)	Sigma σ (cal yrs)	Context of dating
1	140.0–142.5	Moss-fen peat	Needles of <i>Larix decidua</i>	MKL-A6288	9860 ± 33	11,390–11,379 (1.9%), 11,326–11,202 (93.6%)	11,261	38	Within the Younger Dryas chronozone
2	160.0–162.5	Moss-fen peat	Needles of <i>Pinus sylvestris</i>	MKL-A6289	10,395 ± 30	12,479–12,096 (92.9%), 12,086–12,058 (2.6%)	12,279	119	Allerød and Younger Dryas boundary
3	200.0–202.5	Peat intercalated with silt	Needles of <i>Pinus sylvestris</i>	MKL-A6290	11,080 ± 29	13,092–12,918 (95.4%)	13,009	52	Gerzensee oscillation
4	239.5–241.5	Peat intercalated with silt	Needles of <i>Pinus sylvestris</i>	MKL-A6291	11,678 ± 30	13,596–13,475 (95.4%)	13,539	37	Allerød-1 and Allerød-2 boundary
5	260.0–262.5	Organic-clastic sediment	Needles of <i>Pinus sylvestris</i>	MKL-A6130	11,700 ± 31	13,604–13,481 (95.4%)	13,549	39	Beginning of accumulation of peat sequence
6	262.5–265.0	Organic-clastic sediment	Stems of mosses	MKL-A5610	12,253 ± 37	14,761–14,746 (0.8%), 14,324–14,061 (94.6%)	14,190	127	Beginning of accumulation of peat sequence
7	270.0–272.5	Clastic-organic sediment	Needles of <i>Pinus sylvestris</i> , stems of mosses	MKL-A5462	13,353 ± 37	16,228–15,906 (95.4%)	16,068	79	Beginning of accumulation of peat sequence
8	319.0–322.5	Decomposed peat	Fruits of <i>Eleocharis palustris</i> , stems of mosses	MKL-A5463	11,981 ± 35	14,024–13,906 (48.2%), 13,894–13,785 (47.2%)	13,898	75	Centre of the second organic horizon
9	347.5–350.0	Decomposed peat	Stems of mosses	MKL-A5464	12,238 ± 34	14,309–14,059 (95.4%)	14,160	100	Top of the first organic horizon
10	355.0–357.5	Decomposed peat	Stems of mosses	MKL-A5465	12,422 ± 42	14,896–14,277 (95.4%)	14,568	176	Bottom of the first organic horizon

*Laboratory of Absolute Dating in Kraków, Poland, in collaboration with the Center For Applied Isotope Studies, University of Georgia, U.S.A

of sediment fractions, sediment type and statistical parameters of the grain-size distribution according to Folk and Ward's (1957) graphical method were calculated in GRADISTAT software (Blott and Pye 2001). Transport and deposition mechanisms of sediments were determined based on C–M diagram (Passega and Byramjee 1969). The peat-type description was adopted from a previous study (Margielewski 2001), in which it was determined based on plant-tissue analysis and the classification of Tołpa et al. (1967) (Fig. 1 I).

Geochemical analyses

The carbonate content (equivalent of CaCO_3 obtained from CO_2 concentration released in the reaction with 10% HCl) was determined using Scheibler's volumetric method (Loeppert and Suarez 1996). Further, a set of geochemical proxies usually applied in soil research (Wang et al. 2022) was employed. Total carbon and total nitrogen content (TN) were determined by dry combustion using a Vario Micro Cube CHN elemental analyser with TCD detection (Elementar Analysensysteme GmbH, Langenselbold, Germany) (Nelson and Sommers 1996). For most samples (due to the absence of carbonates), the total carbon content was assumed to correspond to the SOC content. However, if carbonates were present, the SOC content was calculated by subtracting the inorganic carbon content ($\text{eqCaCO}_3 \times 0.12$) from the total carbon content. The content of labile forms of mineral phosphorus (P-PO_4), soluble in deionized water, was measured using a spectrophotometric method at a wavelength of 550 nm (Levy and Schlesinger 1999). The content of nitrate nitrogen (N-NO_3) in 1% K_2SO_4 solutions was determined using phenyldisulfonic acid and measuring the absorbance at a wavelength of 410 nm (Gotkiewicz 1983). The content of ammonium nitrogen (N-NH_4) in 1% K_2SO_4 solutions was determined using direct Nesslerization and measuring the absorbance at a wavelength of 436 nm (Gotkiewicz 1983). The contents of P-PO_4 , N-NO_3 and N-NH_4 were determined for the solid material of the sample (pore water was not investigated). Although the content of P and N fractions in peatland deposits is subjected to various syn- and post-depositional processes (Salmon et al. 2021), the potential

relationship with other palaeoecological data was qualitatively investigated. $\text{N-NO}_3/\text{N-NH}_4$ ratios were calculated to reconstruct level of oxygenation (Gotkiewicz 1973). Additionally, a set of elements were measured (Ca, Mg, K, Na, Fe, Mn, Ni, Cu, Zn, Pb) using an Agilent 8900 Triple Quadrupole ICP–MS (Agilent Technologies, USA) instrument (details in ESM; results of the whole analysis will be presented in separate paper), and Fe/Mn ratios were determined to reconstruct redox conditions (Naeher et al. 2013).

Pollen and non-pollen palynomorphs (NPPs) analysis

A standard chemical preparation for palynological analysis (Erdtman 1960; Fægri and Iversen 1989) was applied to each sample (approx. 1 cm^3 of sediment volume). Quantitative analysis of pollen and NPPs included counting pollen grains of trees and shrubs up to at least 600 per sample under a light microscope. Pollen and NPP identification was based on available keys and the reference collection of modern pollen slides (full list in ESM). Percentage pollen data for each given taxon was determined from the sum of arboreal (AP—trees, shrubs and dwarf shrubs) and non-arboreal (NAP—terrestrial herbs) plant pollen given as $\Sigma\text{AP} + \Sigma\text{NAP} = \Sigma\text{P}$. Taxa of spore-producing plants, non-pollen palynomorphs and corroded pollen were excluded from this sum. Percentage data for taxa of these groups were calculated from the $\Sigma\text{P} + \text{sum of grains from a corresponding group} = 100\%$. All calculations and data plotting were done using Tilia software (Grimm 1991).

Macrofossil analysis

The sediment samples, after disaggregation and elimination of humic substances by boiling in water with detergent and KOH, were mildly washed through a 200 μm mesh sieve. Macrofossil examination was performed with a ZEISS Stemi 508 stereomicroscope at 10–16 \times magnifications. Fruits, seeds, plant vegetative fragments and other macrofossil types were identified according to various keys and publications (full list in ESM). The collection of modern diaspores and specimens of fossil flora from the National Biodiversity

Collection of Recent and Fossil Organisms stored at W. Szafer Institute of Botany PAS in Kraków (herbarium KRAM) were also used for comparison. A full list of references for the macrofossil identification (including animal remains of e.g. Ostracoda, Porifera, Chironomidae), botanical nomenclature, phytosociological nomenclature and palaeoecological indicators is given in ESM. Identified plant and animal taxa were grouped according to specific habitats and plotted on the macrofossil diagram using Tilia software (Grimm 1991) as absolute macrofossil counts per sample volume.

Statistical methods and zonation

Cluster analysis was conducted separately for macrofossil and geochemical data to derive two sets of zonation. Pollen data were not possible to analyse due to the depth interval with lack or scarcity of pollen. Plant macrofossil counts were converted to concentrations (per 20 cm³), and subsequently, both macrofossil and geochemical data (SOC, TN, N–NH₄, N–NO₃, P–PO₄, CaCO₃) were transformed by log₁₀(x + 1) function, in which x is a data value (Birks 2014). Constrained incremental sum of squares

cluster analysis (CONISS, Grimm 1987) was applied and the number of statistically significant zones was determined using the broken stick model (Bennett 1996). Moreover, in case of plant macrofossil data CONISS zonation was also established separately for each habitat group of taxa to capture changes within different parts of the basin, and then compiled together into local macrofossil assemblage zones (LMAZ). All calculations were carried out in R version 4.2.2 (R Core Team 2022) and using package Rioja (Juggins 2022). Eventually, the established geochemical and macrofossil zonation were compiled together by qualitative interpretation into five units which reflect the main palaeoecological stages of the Klaklowo landslide-fen development.

Results

Absolute chronology and sedimentation rate

The calculated age-depth model (Fig. 2—here presented only the 250–370 cm depth section of the entire model) is reliable due to the agreement index A_{model} equal to 66%, which exceeds the recommended minimum of 60% for the model robustness (Bronk Ramsey

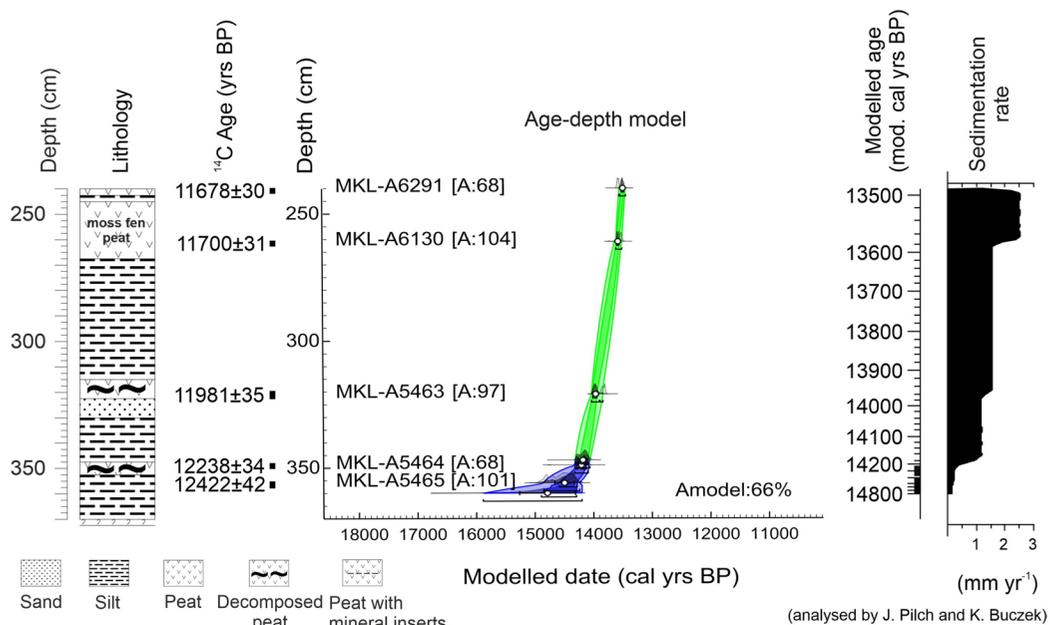


Fig. 2 From the left: lithological column of the Klaklowo fen deposits, uncalibrated ¹⁴C ages of sediment samples, section of the age-depth model presented in this paper (250–370 cm), modelled ¹⁴C age and sedimentation rate

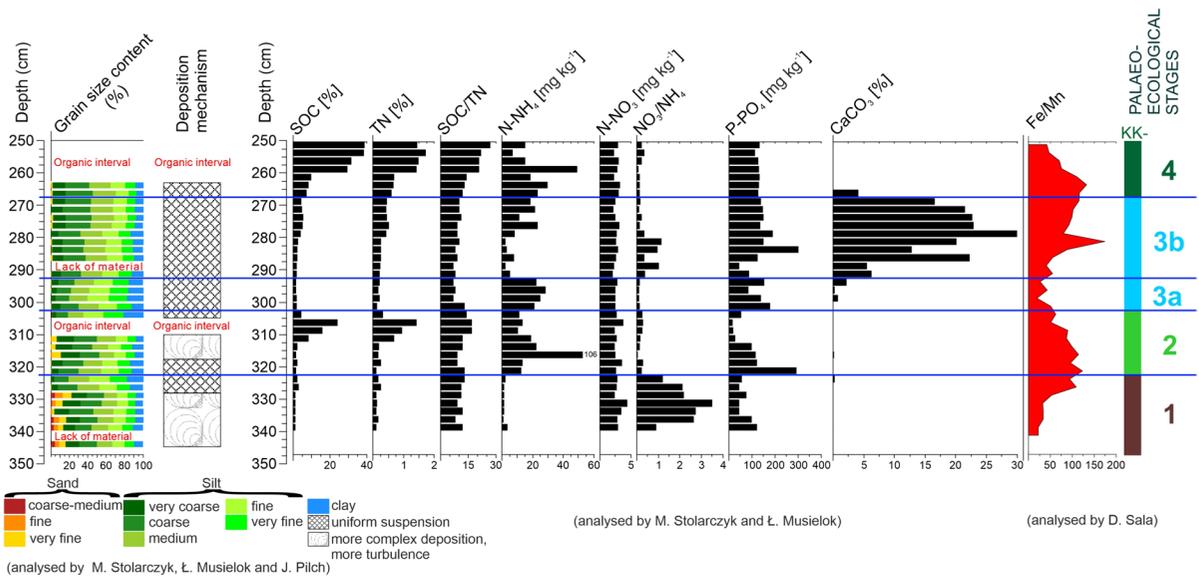


Fig. 3 Sediment-grain size, deposition mechanism and geochemical data of the depth section of 250–350 cm of the Klaklowo landslide-fen deposits

2009). According to the model and AMS dates, the accumulation of organic-minerogenic deposits of the Klaklowo landslide fen began some time before 14,896–14,277 cal yrs BP (the lowermost AMS date). Taking the timeframes between 14,600 mod. cal yrs BP (approximated μ value of the lowermost AMS date) and 13,500 mod. cal yrs BP (approximated μ value from the age-depth model for the depth 250 cm), the accumulation lasted around 1100 mod. years. The sedimentation rate varied throughout the profile, from low: 0.2 mm yr⁻¹ (347–360 cm), through medium: 1.2–1.5 mm yr⁻¹ (261–347 cm), to the highest: 2.5 mm yr⁻¹ above a depth of 261 cm, at which moss fen peat accumulation began.

Grain-size data

Grain-size results show that the minerogenic sediment of the Klaklowo fen sequence can be classified as silt varying from fine to coarse, with noticeable admixture of very fine to medium and coarse sand occurring at a depth of 327.5–345.0 cm and of very fine sand at a depth of 310.0–317.5 cm (Fig. 3). Due to the small variability, a detailed description of sediment types along the profile according to Folk and Ward’s (1957) (ESM–Fig. 2) parameters and interpretation of deposition mechanisms based on C–M

diagram (Passega and Byramjee 1969) (ESM–Fig. 3) are given in the ESM.

Geochemical data

CONISS analysis of the geochemical data allowed to distinguish five geochemical zones corresponding to five palaeoecological stages (Fig. 3; CONISS dendrogram in ESM–Fig. 4). Stage KK-1 (322.5–340.0 cm) was characterized by a relative increase in the content of organic matter and a trace amount of carbonates and a clear dominance of nitrate N over ammonium N, expressed by NO₃/NH₄ values higher than 1, with an average of 2.17. P concentrations in the lowermost zone were characterized by the lowest average value among all analysed zones, amounting to 67.7 mg kg⁻¹. Fe/Mn ratios were also among the lowest (22.4–109.5) of all stages, however, from around 330.0–332.5 cm they started to increase noticeably. Stage KK-2 (302.5–322.5 cm) was characterized by an organic-rich insert (up to 23.9% SOC, 1.1% TN) occurring in the uppermost part, while in the lower part of this zone both SOC and TN showed a gradual decrease with values ranging from 1.3 to 2.2% and from 0.1 to 0.3%, respectively. The upper boundary of the stage KK-2 displayed a

clear decrease in P concentration compared to the stage KK-3, along with a relative increase in P-PO₄ with depth, ranging from 15.5 to 291.2 mg kg⁻¹. Moreover, at a depth of 315.0–317.5 cm, the highest concentration of ammonium N (105.93 mg kg⁻¹) in the entire profile was recorded. Fe/Mn values, with some fluctuations, kept on a high level (average value 95.0) and decreased gradually in the upper part of the zone to 50.7. Stage KK-3a (292.5–302.5 cm) was characterized by trace amounts of carbonates (up to 2.1% eqCaCO₃) occurring in the uppermost part, while the content of other analysed elements was aligned through the whole depth. Similarly to KK-1, Fe/Mn values were low (43.8 on average). Stage KK-3b (267.5–292.5 cm) contained carbonate-rich material (5.4–29.9% eqCaCO₃) which in its upper part showed relatively high content of organic matter (3.8–5.2% SOC and 0.4–0.5% TN). The interval 280.0–285.5 cm showed a relative decrease in N–NH₄ to N–NO₃ concentrations (with an average NO₃/NH₄ ratio of 1.03), coinciding with notably higher concentrations of P–PO₄. Fe/Mn ratio was increasing with decreasing depth (from 26.7 to 102.1), with a sudden rise to the highest value (174.9) in the entire investigated section at a sample depth of 280.0–282.5 cm and a subsequent

drop to lower values. Stage KK-4 (250.0–267.5 cm) was characterized by the highest contents of SOC (7.0–38.5%) and TN (0.6–1.7%). Both elements increased gradually with the decreasing depth. The ratio of N–NO₃ to N–NH₄ was low (0.16 on average), indicating a predominance of ammonium N over nitrate N. The P–PO₄ content was in a range from 110.7 to 133.4 mg kg⁻¹. Fe/Mn ratios continued to increase in the lower part up to the ratio of 132.3, but then started to decrease (to 42.2 in the uppermost sample).

Pollen and NPP data

The conducted pollen analysis showed the absence or strong scarcity of pollen grains along with up to 55% share of corroded pollen in the lowermost part (287.5–367.0 cm) of the investigated Klaklowo sediment sequence. Therefore, distinguishing local pollen assemblage zones (LP AZ) and chronozones was not possible for this depth interval (Fig. 4). Instead, based only on a number of pollen grains found in sediment, three pollen zones were established for the depth section of 250–367 cm (Fig. 4): zone P1 (332.5–367.0 cm)—lack of pollen, zone P2 (287.5–332.5 cm)—poor in pollen, and zone P3 (250.0–287.5 cm)—abundant amount of pollen.

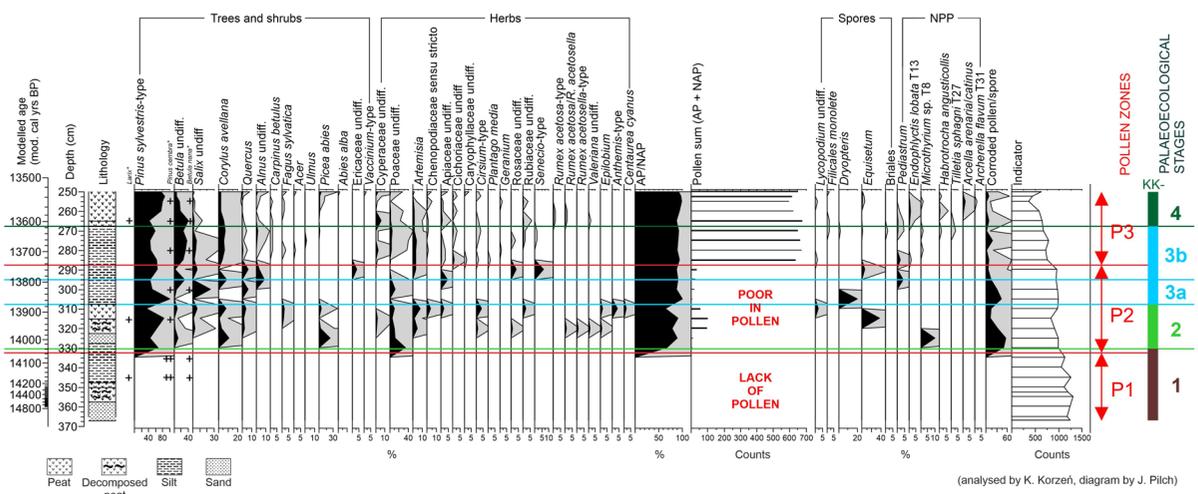


Fig. 4 Pollen-percentage diagram of the depth section 250–367 cm of the Klaklowo landslide-fen deposits. Zonation is represented by three pollen zones and five palaeoecological stages of development. See ESM-Table 1 for detailed description of the zones. Notice that for convenience pollen data from

zone P2 are expressed as percentage data, but it is not interpretable due to pollen scarcity. *occurrence of pollen of *Larix*, *Pinus cembra* and *Betula nana* distinguished in the previous study (Margielewski 2001): +– 1–8 pollen grains; ++ 9–36 pollen grains

Table 2 Palaeoenvironmental reconstruction of stages of the Klaklowo fen development (see also Fig. 6 for summary interpretation)

Palaeoecological stage of the Klaklowo fen development	Description
<p>Stage KK-1 (ca. 14,040–> 14,790 mod. cal yrs BP, ca. > 750 mod. years): Development of the waterbody I after formation of the Klaklowo landslide and sub-scarp depression</p>	<p>Existence of a waterbody during the stage KK-1 is mainly confirmed by the nature of sedimentation of detrital particles from a complex uniform suspension in water and possibly also with some elements of graded suspension (sorting by bottom current) (Fig. 3)—both mechanisms are characteristic for low turbulence conditions. Clastic sedimentation and reduction in biomass input is also reflected in the very low contents of SOC and TN (Fig. 3) (Zeng et al. 2017). Low redox conditions in this zone are indicated by low Fe/Mn ratios and N–NO₃/N–NH₄ ratios higher than 1 (Fig. 3) (Gotkiewicz 1973; Naeher et al. 2013). Sand and debris material from the bottom part of the fen deposits reflect the dynamic slope processes around the Klaklowo sub-scarp depression possibly intensified by the lack of vegetation cover within the freshly formed landslide colluvium (Fig. 3)</p> <p>The Klaklowo waterbody I was oligo- to mesotrophic, only sparsely inhabited by aquatic plants, and it underwent a process of shallowing with development of a fen (decomposed peat containing <i>Bryales</i> sp. — according to Margielewski 2001; macrofossils were dominated by <i>Juncus</i> sp.) and some drainage and desiccation event at a depth of ca. 350 cm (Figs. 5 and 6). This zone is devoid of pollen (zone P1) (Figs. 4 and 6)</p> <p>Arctic/alpine plant species (<i>Dianthus glacialis</i>, <i>Arabis alpina</i>) redeposited to the Klaklowo basin during the stage KK-1 are characteristic for dry and cold conditions of steppe-tundra, within which some tree-shrub stands (<i>Larix decidua</i>, <i>Pinus sylvestris</i>, <i>Betula humilis</i>) probably occurred (Fig. 5). Based on abundant charcoal fragments found, events of palaeo-fires were also common</p>
<p>Stage KK-2 (ca. 13,870–14,040 mod. cal yrs BP, ca. 170 mod. years): Basin drainage and formation of a short-lasting fen</p>	<p>In the lowest part of KK-2 a layer of noticeably coarser sediment (Fig. 3) and a high abundance of sclerotia of <i>Cenococcum geophilum</i> (Fig. 5), again suggest the intensification of slope processes. Within this depth interval of elevated turbulence, an insert of exceptionally high concentrations of N–NH₄ occurs (Fig. 3, 315.0–317.5 cm), suggesting that this N fraction may have allochthonous origin and might be re-reposited to the palaeo-pond from catchment area, e.g. with enhanced surficial flow</p> <p>Plant macrofossils redeposited to the basin during stage KK-2 (<i>Dryas octopetala</i>, <i>Poa</i> cf. <i>alpina</i>, <i>Androsace</i> cf. <i>chamaejasme</i>, to lesser degree: <i>Parnassia palustris</i> and <i>Melandrium rubrum</i>) are again representative for cold and dry habitat of steppe-tundra (Fig. 5). The peat horizon occurring in the zone KK-2 is expressed as an increase in SOC and TN values (Fig. 3) suggesting the enhanced biological production and biomass input (Zeng et al. 2017). Peat-forming plant taxa (<i>Bryales</i> sp. and <i>Carex</i> sp.—according to Margielewski 2001) entered the shallowing Klaklowo waterbody I creating a short-lasting fen. A high decomposition degree of plant macro-remains is evidence for further basin drainage and peat rotting (Fig. 5). Enhanced input from boggy and terrestrial plants is also reflected in slightly higher SOC/TN ratios (Fig. 3). Decomposed peat layer is also characterized by the lowered values of N–NH₄ and P–PO₄, suggesting a decrease rather than intensification of mineralization processes, which would be expected in conditions of a lowered water table (Zeng et al. 2017). According to Gotkiewicz (1996), moisture content above 75–80% significantly inhibits mineralization and reduces especially the release of nitrates</p> <p>The dominating occurrence of the boggy taxa <i>Valeriana simplicifolia</i>, <i>Carex rostrata</i>, <i>Carex diandra</i>, <i>Eleocharis palustris</i> and <i>Phragmites australis</i> suggests water depth less than 1 m with the interannual fluctuations of 1 m (Gaillard and Birks 2007) and perhaps some pools with standing water (Characeae) (Fig. 5). plant-taxa composition suggests that conditions in the fen were mostly eutrophic (with trend to mesotrophic) and neutral to alkaline (for <i>Carex</i> sp. with trend to acidic). As indicated by Fe/Mn ratios, during stage KK-2, low redox conditions prevailed, decreasing toward the upper boundary. This zone is poor in pollen (zone P2) (Figs. 4 and 6)</p>

Table 2 (continued)

Palaeoecological stage of the Klaklowo fen development	Description
Stage KK-3a (ca. 13,790–13,870 mod. cal yrs BP, ca. 80 mod. years): Colonization of waterbody II	Abundant presence of aquatic plants (Fig. 5) and sedimentation of coarse silt from uniform suspension (no sorting by bottom current) (Fig. 3) indicate that during this stage, a waterbody developed once again and was subsequently colonized mostly by Characeae and other macrophytes. Palaeo-pond probably possessed a (eulittoral) zone with boggy plant taxa (<i>Carex</i> sp. and <i>Scirpus sylvaticus</i> but with Bryopsida mosses withdrawal) and was surrounded by some tree patches of <i>Larix decidua</i> , <i>Pinus sylvestris</i> and <i>Betula</i> sp. The expansion of Characeae implies alkaline and oligo- to mesotrophic conditions. In this zone, elevated contents of P-PO ₄ and N-NH ₄ correspond to elevated oxygenation of the environment (Fig. 3). This stage is also poor in pollen (zone P2) (Figs. 4 and 6)
Stage KK-3b (ca. 13,620–13,790 mod. cal yrs BP, ca. 170 mod. years): Waterbody II overgrowing	<p>Accumulation of coarse silt continued in the Klaklowo waterbody II throughout the stage KK-3b. The prominent feature of this zone is precipitation of carbonates: CaCO₃ content increases gradually from the lower boundary of KK-3b to a maximum carbonate concentration at a depth of 277.5–280.0 cm, and then it decreases at slower pace upward to the upper boundary of KK-3b at which it sharply ends (Figs. 3, 5 and 6). Parallel, the oxygenation level is decreasing. In the same depth interval, vast submerged Characeae meadows spread at the bottom of the waterbody (Figs. 5 and 6). Carbonate precipitation was also expressed in the form of calcified oospores (gyrogonites) (Apolinarska et al. 2011) abundantly found in this sediment interval. Characeae presence and precipitation of carbonates indicate that the local aquatic environment was alkaline. Moreover, presumably water was also well-transparent and oligo- to mesotrophic. Other macrophyte representatives (<i>Potamogeton pusillus</i>, <i>Myriophyllum verticillatum</i> and <i>Hippuris vulgaris</i>) confirm the alkaline conditions, however, they can thrive also in more eutrophic waterbodies</p> <p>Clastic sedimentation in the palaeo-pond II is also expressed in low values of SOC and TN, however, they slightly increase with the decreasing depth. This increase may signalize the beginning of organic matter accumulation in situ by vegetation overgrowing the pond as well as possibly from external delivery of terrestrial organic material to the pond (Zeng et al. 2017). A growing number of macrofossils of <i>Betula nana</i>, <i>Betula pubescens</i>, <i>Carex rostrata</i>, <i>Carex diandra</i> and Bryopsida mosses during this stage also reflects the terrestrial plants succession (<i>Betula</i>-dominated boreal forest). These plant taxa point at oligotrophic-mesotrophic conditions and moderately acidic soils around palaeo-pond (in case of <i>Betula nana</i> even highly acidic)</p> <p>Moreover, during this stage the abundant amount of pollen is finally recorded (Fig. 4), probably coupled with vegetation development. It is characterized by predominance of AP vs NAP vegetation, with highest percentage of <i>Pinus sylvestris</i> (ca. 40–80%) and <i>Betula</i> undiff. (ca. 25–40%). The pollen curves of these taxa stay in agreement with macrofossil results: in the 267.5–287.5 cm interval the progression of <i>Betula</i> undiff. can be observed, whereas <i>Pinus sylvestris</i> slightly declines. Among pollen curves of herbs, Cyperaceae also show an increase. Among NPP <i>Pediastrum</i> is present, confirming the aquatic conditions</p> <p>Apart from the occurrence of <i>Dryas octopetala</i>, Asteraceae and some minor amounts of Poaceae, non-arboreal indicators of dry and cold conditions are absent in this zone, but some areas of dry open-land habitat probably still occurred in the vicinity of the Klaklowo waterbody (Fig. 5)</p>

Table 2 (continued)

Palaeoecological stage of the Klaklowo fen development	Description
Stage KK-4 (< 13,530–13,620 mod. cal yrs BP, ca. > 90 mod. years): Waterbody II transition to a long-lasting fen	This stage documents a transition from Klaklowo palaeo-pond II into a long-lasting Klaklowo fen, which is also confirmed by results of previous plant-tissue analysis of the Klaklowo sediment core, indicating the formation of moss-fen peat (<i>Bryalo-Parvocariconi bryalet</i> consisting of <i>Phragmites australis</i> and <i>Bryales</i> mosses—according to Margielewski 2001). Organic material accumulation is also expressed as gradually increasing SOC and TN values and other geochemical data (Fig. 3). Increasing SOC/TN ratios indicate the increased input from boggy and terrestrial plants (Meyers and Ishiwatari 1993) In the catchment of the Klaklowo fen a boreal forest dominated by <i>Pinus sylvestris</i> started prevailing at that time (probably outcompeting <i>Betula nana</i> and <i>Betula pubescens</i>) (Figs. 5 and 6). The fen was water-logged (decreasing oxygenation indicated by increasing Fe/Mn ratios, Fig. 3) and probably mesotrophic, however, in the upper part of the zone sedges (<i>Carex</i> sp.) and Bryopsida mosses were also gradually diminishing (Figs. 5 and 6). Instead, plant taxa of slightly different conditions started to occur sporadically (<i>Taraxacum officinale</i> , <i>Caltha palustris</i> , <i>Glyceria maxima</i>) perhaps suggesting another change to more alkaline and eutrophic conditions in the Klaklowo fen

Detailed description of these zones can be found in ESM-Table 1. Results essential for interpretation are summarized in Table 2 and Fig. 6.

Macrofossil data

CONISS analysis performed separately for each plant ecological group allowed to eventually compile eleven LMAZ units (CONISS dendrograms in ESM-Fig. 5a–e). A detailed description of LMAZ and local palaeoecological interpretation, divided into five palaeoecological stages is given in ESM-Table 2. A macrofossil diagram divided into stages from KK-1 to KK-4 is presented in Fig. 5. Data essential for interpretation are summarized in Table 2 and Fig. 6.

Discussion

Palaeoecological development stages of the Klaklowo fen in the light of palaeoclimatic interpretation and correlation with extraregional chronologies

Based on the result of multi-proxy analysis and zonation of geochemical and macrofossil data derived from cluster analysis, five palaeoecological stages of the Klaklowo landslide-fen development were ultimately distinguished for the investigated late glacial deposits of the fen (a depth interval of 250–367 cm, time span: ca. 14,600 and 13,500 mod. cal yrs BP).

Detailed palaeoenvironmental reconstruction of these stages is given in Table 2, whereas an interpretation summary and the most essential proxies are shown in Fig. 6.

Palaeoclimatic conditions inferred from established palaeoecological stages revealed a general change from colder to warmer climate. As indicated by macrofossils of Arctic/alpine plant species (*Dianthus glacialis*, *Arabis alpina*; Fig. 5) during stage KK-1, dry and cold conditions of steppe-tundra prevailed in the surroundings of the presumably periodical and oligotrophic Klaklowo waterbody I (Fig. 6). Occurrence of *Parnassia palustris* suggests minimum mean July temperatures around 7 °C (Aalbersberg and Litt 1998).

Stage KK-2 is also characterized by cold and dry climate (macrofossils of: *Dryas octopetala*, *Poa* cf. *alpina*, *Androsace* cf. *chamaejasme*), and moreover—as a number of determined taxa specific to these conditions is higher than for the stage KK-1—steppe-tundra was probably even more wide-spread around the Klaklowo basin (Figs. 5 and 6). Plant taxa associated with formation of a short-lasting fen (*Parnassia palustris*, *Eriophorum vaginatum*, *Eleocharis palustris*) point at minimum mean July temperatures around 7–10 °C (Aalbersberg and Litt 1998).

Characeae and other macrophytes colonised the Klaklowo waterbody II during the stages of KK-3a and KK-3b prior to the terrestrial plant succession

recorded during stages KK-3b and KK-4 (Figs. 5 and 6). Taxa of aquatic plants found in this zone include *Batrachium* sp., *Potamogeton pusillus*, *Myriophyllum verticillatum* and *Hippuris vulgaris* suggesting minimum mean July temperatures > 10 °C (optimum: > 13 °C) (Aalbersberg and Litt 1998; Gaillard and Birks 2007). Soon after, the birch-dominated boreal forest developed in the Klaklowo waterbody catchment, with *Betula nana* indicating the minimum mean July temperatures 7 °C and *Carex rostrata*—around 8 °C (Aalbersberg and Litt 1998). Pioneering aquatic and subsequent terrestrial plant succession (boreal forest) signalizes warming and moistening of the climate (Iversen 1954).

During stage KK-4, the Klaklowo palaeo-pond was transformed into a minerogenic fen dominated by Bryidae mosses (moss fen peat *Bryalo-Parvocariconi bryalet* consisting of *Phragmites australis* and *Bryales* pl. sp. — according to Margielewski 2001), whereas the boreal forest became predominated by *Pinus sylvestris*. The abundant presence of pioneering species *Pinus* and *Betula* reflects their expansion and rising production of pollen and fruits due to elevated temperatures (Feurdean et al. 2007), confirming the ongoing climatic warming (Figs. 4, 5 and 6).

Vegetation changes of the stages KK-3 and KK-4 observed consistently both in macrofossil (Figs. 5 and 6) and pollen data (Figs. 4 and 6) seem to correspond to the climate warming of Allerød—then this climatic amelioration took place earlier than established by previous pollen-based chronozones (Margielewski 2001) (Figs. 1 I and 6). Based on the obtained Klaklowo radiocarbon absolute chronology (Fig. 2) in reference to different extraregional chronologies, the late glacial sequence of the Klaklowo fen in a greater can be correlated in a greater extent with the Greenland ice core record (Rasmussen et al. 2014) and the Gerzensee Lake deposits, Switzerland (Ammann et al. 2013), than with the Meerfelder Maar deposits, Eifel region, Germany (Litt et al. 2001) (Fig. 6). According to NGRIP and Gerzensee chronologies, stage KK-1 corresponds to the Oldest Dryas climate cooling and Bølling climate warming, stage KK-2 to the Older Dryas cooling, whereas stages KK-3a, KK-3b and KK-4 correspond to the Allerød warming. In the light of data collected in the current research, previous stratigraphic position of the supposed Older Dryas deposits (Margielewski 2001) cannot be confirmed, however, attribution of the stage KK-2 to the Older

Dryas climate cooling should be done with caution (Rasmussen et al. 2014).

Characeae-dominated aquatic organisms' response to alkalinity changes, boreal forest development and pond overgrowing

Characeae meadows development

A high content of calcium carbonate (5.4–29.9% eqCaCO₃) in the Klaklowo deposits during the stage KK-3b (267.5–295.0 cm) correlates with the abundant macrofossils of Characeae meadows (around 2000 estimated oospores per sample) as well as with the presence of other macrophytes (*Potamogeton pusillus*; *Myriophyllum verticillatum* and *Hippuris vulgaris*, Figs. 5 and 6). This co-occurrence indicates that alkaline conditions and intense autochthonous precipitation of carbonates prevailed in the water of the Klaklowo palaeo-pond II at that time (Kufel and Kufel 2002; Pelechaty et al. 2013). In lakes, autochthonous production of CaCO₃ by phytoplankton and macrophytes results from their photosynthetic activity, i.e. the assimilation of CO₂ from inorganic carbon source—the bicarbonates dissolved in water. Moreover, calcium concentration was found as one of the most essential variable affecting the distribution of Characeae habitats in the area of present-day Europe and USA (Sleith et al. 2018). Carbonate ions are also utilized by Ostracoda (aquatic crustaceans) to build their shells and their presence in the Klaklowo sedimentary record also corresponds to the depth range of CaCO₃ and Characeae occurrence (Fig. 6). It is, however, important to notice that although most freshwater species of ostracods thrive in alkaline or slightly acidic waters, some of them show a wide range of pH tolerance (Ruiz et al. 2013).

Research on lakes of various age formed in recently deglaciated areas showed that with a lake development, a decline of pH, alkalinity and rise in dissolved organic carbon can be observed, as a result of hydrologic change, vegetational succession and soil formation in the catchment area (Engstrom et al. 2000). Calcium and bicarbonate ions can be available for carbonate precipitation from leaching of bedrock in the catchment area. Within geologic formations occurring in the Klaklowo fen basin, sandstones, mudstones and shales with calcareous

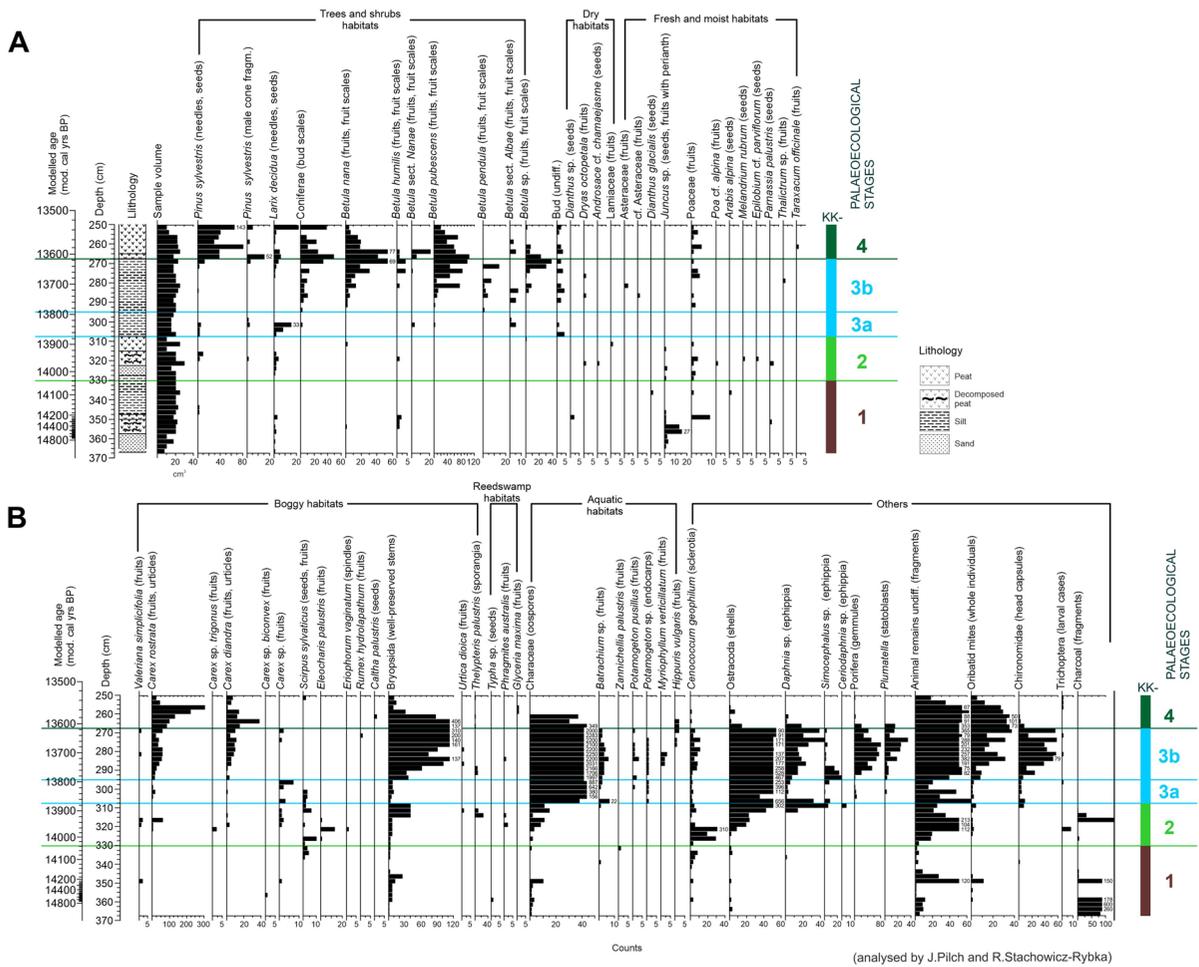


Fig. 5 **A** and **B** Macrofossil diagram of the depth section 250–367 cm of the Klaklwo landslide-fen deposits divided into parts according to ecological groups (habitats). Values are absolute counts per sample (sample volumes presented on the left)

cements as well as marls (Książkiewicz et al. 2016) may constitute a possible source of these ions (ESM Fig. 1). Moreover, rising temperatures and precipitation of the Allerød climatic phase possibly triggered changes in water circulation and chemistry (Margielewski et al. 2022b), and intensified leaching processes. The access to carbonate ions likely resulted from the groundwater supply, because the Klaklwo palaeo-pond was probably (similarly to the subsequently formed Klaklwo fen) characterized by complex recharge system including surface flow, subsurface storm flow and direct influx to landslide depression from shallow aquifer (Margielewski 2001). Additional factors that influenced the water chemistry of tundra lakes possibly included

permafrost degradation in the catchment area, which led to elevated ion concentrations and improved water transparency, and subsequently allowed for colonization by characean algae and other aquatic plants (Mesquita et al. 2010).

Decline of Characeae meadows and other aquatic organisms

In the middle of the stage KK-3b (at a depth of 277.5–280.0 cm) a peak of calcium carbonate content was observed, with concentrations gradually diminishing further upward in the sediment profile. At a depth of ca. 267.5 cm carbonate precipitation ended, whereas Characeae oospores abruptly drop in number

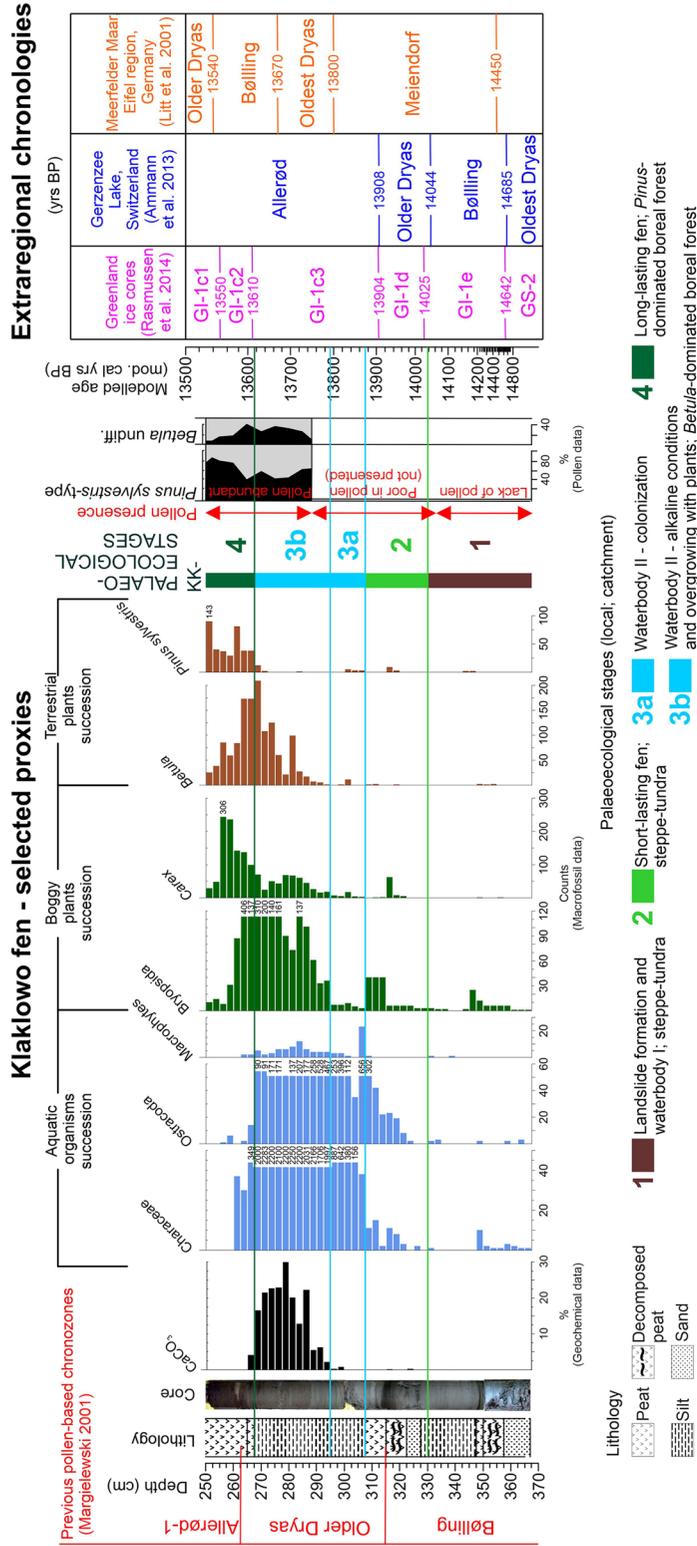


Fig. 6 Selected proxies and summary interpretation of the palaeoecological stages of the Klaklowo landslide-fen development compiled with previous pollen-based stratigraphy and other extraregional chronologies spanning 14,600–13,500 cal yrs BP. Columns with macrofossil data of macrophytes, *Carex* and *Betula* show a sum of macrofossil counts determined for the species belonging to these groups

and soon after this macroalgae group, along with other macrophytes, disappeared from the Klaklowo palaeo-pond II (Fig. 6). Furthermore, withdrawal of aquatic plants coincided with the spreading of boggy and terrestrial plants (development of boreal forest dominated by birch) and the overgrowing of palaeo-pond II revealed by macrofossil and pollen data (Figs. 4, 5 and 6). Presence of plant taxa including *Betula nana*, *Betula pubescens*, *Carex rostrata* and *Carex diandra* points at an occurrence of moderately acidic soils (in case of *Betula nana* even highly acidic). The immigration of trees to the Klaklowo catchment, especially conifers during the stage KK-4, probably resulted in enhanced delivery of (acidic) organic substances to the palaeo-pond II which, in turn, affected water chemistry and led to the decline of Characeae meadows and other aquatic organisms (Fallu et al. 2005). Beside acidification caused by vegetation and soil development, another driver which affected the change in carbonate-ion availability and water pH in the Klaklowo palaeo-pond was probably related to a shift in water supply from calcium-rich (high-alkalinity) groundwater inflows to dominance of calcium-depleted (low-alkalinity) overland flow and precipitation (Engstrom et al. 2000). Engstrom et al. (2000) stated that even with a moderate but constant groundwater flow to the lake, water chemistry and buffering capacity remained resistant to the influence of the terrestrial plant succession.

Additional stressors which executed the disappearance of Characeae meadows possibly included some other phenomena: (1) change from oligo-mesotrophic to eutrophic conditions as indicated by some sporadic plant taxa in the zone KK-4 (Fig. 5, Table 2); development of low-oxygenated conditions confirmed by increasing Fe/Mn ratios throughout the stage KK-3b (Fig. 3); increasing shade from terrestrial plants caused by plant primary succession (Figs. 5 and 6); and shallowing of the waterbody due to mineral material/peat accumulation and/or water-level fluctuations (Fig. 6). Characeae retreat was probably also associated with increasing water turbidity due to climatically-driven eutrophication and brownification (Rip et al. 2007; Choudhury et al. 2019).

Discontinuity of the pollen record—possible causes and significance for palaeoenvironmental reconstruction of the Klaklowo waterbody I

Pollen analysis of the Klaklowo fen deposits revealed partial absence and depletion in pollen grains hindering from development of reliable LPAZ and climate-vegetation zonation for the lowest part of the sediment sequence (pollen zones: lack of pollen, poor in pollen and abundant pollen in Figs. 4 and 6). According to a previous study of the Klaklowo landslide fen (Margielewski 2001) in which LPAZ/chronozones were distinguished, the new pollen spectrum has only a slightly greater depth range (ca. 8 cm, to a depth 340 cm), whereas pollen grains are also scarce (ca. 100–200 grains in bottom parts).

Generally, factors controlling pollen content and distribution in aquatic environments include primary productivity of the terrestrial plants, transport to and spreading over the basin, and subsequent degradation. The primary factor influencing pollen decay might be oxidation occurring in different forms at pre-, syn- and post-depositional stages (Carrión et al. 2009). Lacustrine and peatland deposits are usually pollen-bearing, however, pollen-sterile horizons may intercalate the sedimentary sequence as a result of inwash of soil and sandy material already depleted in pollen due to oxidation at pre-depositional stage. This process relates to intensified erosion in the lake/fen surroundings and may be especially valid for the Klaklowo fen deposits during stage KK-1 and the beginning of KK-2 (Fig. 3). For the Tarnowiec site in the Central Western Carpathians, the deposits of the Older Dryas climatic cooling were characterized by low pollen concentration due to high content of minerogenic materials (Harmata 1987). Pollen depletion in such clastic layers may be additionally coupled with decreased primary pollen productivity by plants and sparse vegetation cover during climate deterioration (Fallu et al. 2005). Moreover, in the Pleistocene and Holocene sediment sequences in Europe and North America, decay of pollen grains was commonly observed to be also caused by mechanical damage and oxidizing conditions during fluvial transport (Delcourt and Delcourt 1980; Carrión et al. 2009). Therefore, the pollen-depleted sandy horizon accumulated at the beginning of stage KK-2 (Figs. 3 and 6) could be also attributed to the delivery of high-energy fluvial sediments at the syn-depositional stage.

At post-depositional stage, pollen decomposition may be connected with fluctuations of lake/fen-water level, including the number of wet-dry cycles (oxidation–reduction cycles) and timespan of exposure to sub-aerial conditions (Campbell 1994; Carrión et al. 2009). For the first stage of the Klaklowo landslide-fen development (KK-1), low Fe/Mn ratios and $N-NO_3/N-NH_4$ ratios above 1 (Fig. 3) point to occurrence of aerobic conditions (Gotkiewicz 1973; Naeher et al. 2013), suggesting that Klaklowo waterbody I was characterized by strong fluctuations of water level. Two horizons of decomposed peat (within stage KK-1 and KK-2) resulted from drainage and desiccation events, and are also evidence of a decreasing water table of the Klaklowo palaeo-pond I. Interseasonal and/or interannual periodicity in the palaeo-pond occurrence cannot be excluded as a factor conditioning repetitive oxidation–reduction and subsequent pollen decomposition. Periodical water-level fluctuations were observed, for instance, in the case of a thermokarst lake in the Swiss Alps, which experienced water drainage due to the unfreezing of the lake bottom every year during late spring (Kääb and Haeberli 2001). Therefore, hydrological changes in Klaklowo waterbody were probable also influenced by permafrost. Moreover, interpreting depletion in pollen as a result of water-level fluctuations may become an asset to the palaeoenvironmental reconstruction of the stage KK-1, giving the possible explanation to poor aquatic life determined by macrofossil analysis for the Klaklowo waterbody I.

Conclusions

Presented high-resolution multi-proxy analysis of the Klaklowo fen-sediment sequence allowed us to reconstruct past vegetation, climate and hydrological changes during the late glacial (ca. 14,600–13,500 mod. cal yrs BP). We inferred that:

1. The development of the Klaklowo palaeo-pond was multi-staged (five palaeoecological stages) and included: waterbody I (KK-1), short-lasting fen (KK-2), waterbody II (divided into two sub-stages KK-3a and KK-3b) and a long-lasting fen (KK-4). These stages corresponded to phases of climate-vegetation changes in the palaeo-pond catchment: from steppe-tundra (KK-1

and KK-2) to *Betula*-dominated (KK-3a and KK-3b) and later *Pinus*-dominated boreal forest (KK-4). Based on the Klaklowo radiocarbon absolute chronology correlated with the records of Greenland ice cores and Gerzensee Lake deposits, stage of waterbody I corresponds to the Oldest Dryas climate cooling and Bølling climate warming, the short-lasting fen stage documents the Older Dryas cooling, whereas the aquatic and terrestrial vegetation succession observed for the stages of waterbody II and a long-lasting fen reflect the climate warming of the Allerød.

2. The co-occurrence of macrophytes dominated by wide-spread Characeae meadows and intense precipitation of $CaCO_3$ indicate that alkaline conditions prevailed in the Klaklowo waterbody II at the beginning of the Allerød climate warming. Bicarbonate ions may have derived from (climatically intensified) leaching of carbonate-bearing bedrock in the catchment area which also provided calcium-rich groundwater to the pond. With time, similarly to present-day lakes of tundra and boreal regions, Klaklowo palaeo-pond II probably experienced a reduction of water alkalinity and increased input of (acidic) organic substances as a result of the boggy and terrestrial vegetation succession (especially conifers), soil formation and change of hydrological regime. In addition to acidification, some other phenomena related to the palaeo-pond transition into a fen possibly affected the basin too. Therefore, the disappearance of the Characeae meadows should be attributed to multiple factors.
3. Frequent fluctuations of the water level, characteristic for waterbodies and fens developed within landslide depressions, and resulting oxidation conditions (as inferred from geochemical proxies) were probably one of the most prominent causes of the pollen deterioration during the development of the Klaklowo palaeo-pond I. Other pre-, syn- and post-depositional processes should be also considered. However, the issue of the discontinuous pollen record requires further studies.

Acknowledgements This study was supported with funds from the National Science Centre, Poland, grant No. 2020/39/O/ST10/03504 (2021–2025). We are grateful to

the Doctoral School of Natural and Agricultural Sciences in Kraków for the opportunity to conduct the research project as a PhD thesis. We thank MSc Eng. Andrzej Kalemba (Institute of Nature Conservation Polish Academy of Sciences) for his help during field works, as well as Prof. Krzysztof Lipka from the Agriculture University in Kraków, Poland, for peat-type analysis and Dr. Valentina Zernitskaya from the Institute for Nature Management, National Academy of Sciences, Minsk, Belarus, for pollen analysis carried out during previous studies. We sincerely thank the editor, Professor Steffen Mischke and the anonymous reviewers for their thorough and invaluable comments that led us to greatly improve our manuscript.

Author contribution Field works were done by WM, KB and JP. Sample collection was done by JP. Conceptualization was done by WM, RSR, KB and JP. Supervision was done by WM and RSR. Macrofossil analysis was done by JP and RSR. Age-depth model was prepared by JP and KB. Grain-size analysis was done by ŁM, MS and JP. Geochemical analysis was done by ŁM, MS and DS. Pollen and NPPs analysis was done by KK. Macrofossil, grain size, pollen and geochemical data processing and visualization was done by JP. Statistical analysis was done by JP. Palaeoenvironmental interpretation was done by JP, WM, RSR and KB. Writing—original draft was prepared by JP. Writing—editing was done by JP, WM, RSR, KB, MS and ŁM. All authors reviewed the manuscript.

Data availability The data will be made available on request.

Declarations

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Aalbersberg G, Litt T (1998) Multiproxy climate reconstructions for the Eemian and Early Weichselian. *J Quat Sci* 13:367–390
- Ammann B, van Leeuwen JFN, van der Knaap WO, Lischke H, Heiri O, Tinner W (2013) Vegetation responses to rapid warming and to minor climatic fluctuations during the Late-Glacial Interstadial (GI-1) at Gerzensee (Switzerland). *Palaeogeogr Palaeoclimatol Palaeoecol* 391:40–59
- Apolinarska K, Pelechaty M, Pukacz A (2011) CaCO₃ sedimentation by modern charophytes (Characeae): can calcified remains and carbonate $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ record the ecological state of lakes?—a review. *Stud Limnol Telmatologica* 5:55–66
- Bennett KD (1996) Determination of the number of zones in a biostratigraphical sequence. *New Phytol* 132:155–170
- Birks HJB (2014) Challenges in the presentation and analysis of plant-macrofossil stratigraphical data. *Veg Hist Archaeobot* 23:309–330
- Blott SJ, Pye K (2001) Technical communication GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surf Process Landforms* 26:1237–1248
- Bronk Ramsey C (2009) Bayesian analysis of radiocarbon dates. *Radiocarbon* 51:337–360
- Campbell I (1994) Pollen preservation in lake sediments: repeated wet-dry cycles in saline and fresh-water sediments. *Palynology* 18:5–10
- Carrión JS, Fuentes N, González-Sampérez P, Sánchez Quirante L, Finlayson JC, Fernández S, Andrade A (2007) Holocene environmental change in a montane region of southern Europe with a long history of human settlement. *Quat Sci Rev* 26:1455–1475
- Carrión JS, Fernández S, González-Sampérez P, Leroy SAG, Bailey GN, López-Sáez JA, Burjachs F, Gil-Romera G, García-Antón M, Gil-García MJ, Parra I, Santos L, López-García P, Yll EI, Dupré M (2009) Quaternary pollen analysis in the Iberian Peninsula: the value of negative results. *Internet Archaeol* 25:1–53
- Choudhury MI, Urrutia-Cordero P, Zhang H, Ekvall MK, Medeiros LR, Hansson LA (2019) Charophytes collapse beyond a critical warming and brownification threshold in shallow lake systems. *Sci Total Environ* 661:148–154
- Delcourt PA, Delcourt HR (1980) Pollen preservation and Quaternary environmental history in the Southeastern United States. *Palynology* 4:215–231
- Engstrom DR, Fritz SC, Almendinger JE, Juggins S (2000) Chemical and biological trends during lake evolution in recently deglaciated terrain. *Nature* 408:161–166
- Erdtman G (1960) Acetolysis method. A revised description. *Sven Bot. Tidskr* 54:561–564
- Fægri K, Iversen J (1989) Textbook of pollen analysis, 4th edn. John Wiley & Sons, Chichester
- Fallu MA, Pienitz R, Walker IR, Lavoie M (2005) Paleolimnology of a shrub-tundra lake and response of aquatic and terrestrial indicators to climatic change in arctic Québec, Canada. *Palaeogeogr Palaeoclimatol Palaeoecol* 215:183–203
- Feurdean A, Wohlfarth B, Björkman L, Tantau I, Bennike O, Willis KJ, Farcas S, Robertsson AM (2007) The influence of refugial population on Lateglacial and early Holocene vegetational changes in Romania. *Rev Palaeobot Palynol* 145:305–320
- Folk RL, Ward WC (1957) Brazos River bar: a study in the significance of grain size parameters. *J Sediment Petrol* 27:3–26
- Gaillard M-J, Birks HH (2007) Paleolimnological applications. In: Elias SA (ed) *Encyclopedia of Quaternary Science*,

- Volume 3, 2nd ed. Elsevier Science, Amsterdam, pp 2337–2356
- Gotkiewicz J (1973) Wpływ procesu murszenia gleby torfowej na wielkość stosunku azotu azotanowego do amonowego. *Zesz Probl Postępów Nauk Rol* 146:125–138 (in Polish)
- Gotkiewicz J (1996) Uwalnianie i przemiany azotu mineralnego w glebach hydrogenicznych. *Zesz Probl Postępów Nauk Rol* 440:121–129 (in Polish)
- Gotkiewicz J (1983) Zróżnicowanie intensywności mineralizacji azotu w glebach organicznych związane z odrębnością warunków siedliskowych. Instytut Melioracji i Użytków Zielonych, Falenty (in Polish)
- Grimm EC (1987) CONISS: a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Comput Geosci* 13:13–35
- Grimm EC (1991) TILIA and TILIA graph. Illinois State Museum, Springfield
- Hargeby A, Blindow I, Hansson LA (2004) Shifts between clear and turbid states in a shallow lake: multi-causal stress from climate, nutrients and biotic interactions. *Arch Hydrobiol* 161:433–454
- Harmata K (1987) Late-Glacial and Holocene history of vegetation at Roztoki and Tarnowiec near Jasło (Jasło-Sanok Depression). *Acta Palaeobot* 27:43–65
- Iversen J (1954) The late-glacial flora of Denmark and its relation to climate and soil. *Danmarks Geol Undersøgelser II Række* 80:87–119
- Juggins S (2022) Rioja: analysis of quaternary science data. R package version 1.0–5, <https://cran.r-project.org/package=rjoja>
- Kääb A, Haerberli W (2001) Evolution of a high-mountain thermokarst lake in the Swiss Alps. *Arctic Antarct Alp Res* 33:385–390
- Książkiewicz M, Rączkowski W, Wójcik A (2016) Szczegółowa Mapa Geologiczna Polski w skali 1:50000, Arkusz Osielec. Ministerstwo Środowiska, Warszawa (in Polish)
- Książkiewicz M (1972) Karpaty. In: Pożaryski W (ed) *Budowa geologiczna Polski, part IV, Tektonika*. vol. 3, Karpaty. Wydawnictwo Geologiczne, Warszawa, p 228 (in Polish)
- Kufel L, Kufel I (2002) *Chara* beds acting as nutrient sinks in shallow lakes—a review. *Aquat Bot* 72:249–260
- Levy ET, Schlesinger WH (1999) A comparison of fractionation methods for forms of phosphorus in soils. *Biogeochemistry* 47:25–38
- Litt T, Brauer A, Goslar T, Merkt J, Balaga K, Müller H, Ralska-Jasiewiczowa M, Stebich M, Negendank JFW (2001) Correlation and synchronisation of Lateglacial continental sequences in northern central Europe based on annually laminated lacustrine sediments. *Quat Sci Rev* 20:1233–1249
- Loeppert RH, Suarez DL (1996) Carbonate and gypsum. In: Sparks D (ed) *Methods of Soil Analysis. Part 3. Chemical Methods*. SSSA Book Series vol. 5. SSSA and ASA, Madison, Wisconsin, pp 437–474
- Margielewski W (2001) Late Glacial and Holocene climatic changes registered in forms and deposits of the Klakłowo landslide (Beskid Średni Range, Outer Carpathians). *Stud Geomorphol Carpatho-Balcanica* 35:63–79
- Margielewski W (2018) Landslide fens as a sensitive indicator of paleoenvironmental changes since the Late Glacial: a case study of the Polish Western Carpathians. *Radiocarbon* 60:1199–1213
- Margielewski W, Obidowicz A, Pelc S (2003) Late Glacial-Holocene peat bog on Kotoń Mt. and its significance for reconstruction of palaeoenvironment in the Western Outer Carpathians (Beskid Makowski Range, South Poland). *Folia Quat* 74:35–56
- Margielewski W, Krapiec M, Kupryjanowicz M, Fiłoc M, Buczek K, Stachowicz-Rybka R, Obidowicz A, Pocięcha A, Szychowska-Krapiec E, Sala D, Klimek A (2022a) Bog pine dendrochronology related to peat stratigraphy: palaeoenvironmental changes reflected in peatland deposits since the Late Glacial (case study of the Imszar raised bog, Northeastern Poland). *Quat Int* 613:61–80
- Margielewski W, Obidowicz A, Zernitskaya V, Korzeń K (2022b) Late Glacial and Holocene palaeoenvironmental changes recorded in landslide fens deposits in the Polish Outer Western Carpathians (Southern Poland). *Quat Int* 616:67–86
- Margielewski W, Krapiec M, Buczek K, Szychowska-Krapiec E, Korzeń K, Niska M, Stachowicz-Rybka R, Wojtal AZ, Mroczkowska A, Obidowicz A, Sala D, Drzewicki W, Barniak J, Urban J (2024) Hydrological variability of middle European peatland during the Holocene, inferred from subfossil bog pine and bog oak dendrochronology and high-resolution peat multiproxy analysis of the Budwity peatland (northern Poland). *Sci Total Environ* 931:172925
- Mesquita PS, Wrona FJ, Prowse TD (2010) Effects of retrogressive permafrost thaw slumping on sediment chemistry and submerged macrophytes in Arctic tundra lakes. *Freshw Biol* 55:2347–2358
- Meyers PA, Ishiwatari R (1993) Lacustrine organic geochemistry - an overview of indicators of organic matter sources and diagenesis in lake sediments. *Org Geochem* 20:867–900
- Mirek Z (2013) Altitudinal vegetation belts of the Western Carpathians. In: Obidowicz A, Madeyska E, Turner C (eds) *Postglacial history of vegetation in the Polish part of the Western Carpathians based on isopollen maps*. W. Szafer Institute of Botany, Polish Academy of Sciences, pp 15–21
- Naeher S, Gilli A, North RP, Hamann Y, Schubert CJ (2013) Tracing bottom water oxygenation with sedimentary Mn/Fe ratios in Lake Zurich, Switzerland. *Chem Geol* 352:125–133
- Nelson DW, Sommers LE (1996) Total carbon, organic carbon, and organic matter. In: Sparks D (ed) *Methods of Soil Analysis. Part 3. Chemical Methods*. SSSA Book Series vol. 5. SSSA and ASA, Madison, Wisconsin, pp 961–1010
- Passega R, Byramjee R (1969) Grain size image of clastic deposits. *Sedimentology* 13:233–252
- Pelechaty M, Pukacz A, Apolinarska K, Pelechata A, Siepak M (2013) The significance of *Chara* vegetation in the precipitation of lacustrine calcium carbonate. *Sedimentology* 60:1017–1035
- R Core Team (2022) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria, <https://www.R-project.org/>
- Rasmussen SO, Bigler M, Blockley SP, Blunier T, Buchardt SL, Clausen HB, Cvijanovic I, Dahl-Jensen D, Johnsen SJ, Fischer H, Gkinis V, Guillevic M, Hoek WZ, Lowe JJ,

- Pedro JB, Popp T, Seierstad IK, Steffensen JP, Svensson AM, Vallenga P, Vinther BM, Walker MJC, Wheatley JJ, Winstrup M (2014) A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy. *Quat Sci Rev* 106:14–28
- Reimer PJ, Austin WEN, Bard E, Bayliss A, Blackwell PG, Bronk Ramsey C, Butzin M, Cheng H, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Hajdas I, Heaton TJ, Hogg AG, Hughen KA, Kromer B, Manning SW, Muscheler R, Palmer JG, Pearson C, Van Der Plicht J, Reimer RW, Richards DA, Scott EM, Southon JR, Turney CSM, Wacker L, Adolphi F, Büntgen U, Capano M, Fahrni SM, Fogtmann-Schulz A, Friedrich R, Köhler P, Kudsk S, Miyake F, Olsen J, Reinig F, Sakamoto M, Sookdeo A, Talamo S (2020) The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon* 62:725–757
- Rip WJ, Ouboter MRL, Los HJ (2007) Impact of climatic fluctuations on Characeae biomass in a shallow, restored lake in the Netherlands. *Hydrobiologia* 584:415–424
- Ruiz F, Abad M, Bodergat AM, Carbonel P, Rodríguez-Lázaro J, González-Regalado ML, Toscano A, García EX, Prenda J (2013) Freshwater ostracods as environmental tracers. *Int J Environ Sci Technol* 10:1115–1128
- Salmon VG, Brice DJ, Bridgham S, Childs J, Graham J, Griffiths NA, Hanson PJ (2021) Nitrogen and phosphorus cycling in an ombrotrophic peatland: a benchmark for assessing change. *Plant Soil* 466:649–674
- Sleith RS, Wehr JD, Karol KG (2018) Untangling climate and water chemistry to predict changes in freshwater macrophyte distributions. *Ecol Evol* 8:2802–2811
- Słowiński M, Marcisz K, Płóciennik M, Obremska M, Pawłowski D, Okupny D, Słowińska S, Borówka R, Kittel P, Forysiak J, Michczyńska DJ, Lamentowicz M (2016) Drought as a stress driver of ecological changes in peatland—A palaeoecological study of peatland development between 3500 BCE and 200 BCE in central Poland. *Palaeogeogr Palaeoclimatol Palaeoecol* 461:272–291
- Tołpa S, Jasnowski M, Pałczyński A (1967) System genetyczny klasyfikacji torfów występujących w złożach Europy Środkowej. *Zesz Probl Postępów Nauk Rol* 76:27–99 (in Polish)
- Tomczyk AM, Bednorz E (eds) (2022) Atlas klimatu Polski (1991–2020). Bogucki Wydawnictwo Naukowe, Poznań (in Polish)
- Wang D, Zang S, Wang L, Ma D, Li MS (2022) Effects of permafrost degradation on soil carbon and nitrogen cycling in permafrost wetlands. *Front Earth Sci* 10:1–10
- Zeng M, Zhu C, Song Y, Ma C, Yang Z (2017) Paleoenvironment change and its impact on carbon and nitrogen accumulation in the Zoige wetland, northeastern Qinghai-Tibetan Plateau over the past 14,000 years. *Geochem, Geophys Geosystems* 18:1775–1792

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

1 Electronic Supplementary Materials to:

2 **Characeae-dominated vegetation succession as a key to understanding the**
3 **late glacial environmental changes (ca. 14,600-13,500 cal yrs BP) – a multi-**
4 **proxy record of palaeo-waterbody developed within the Klaklowo landslide, the**
5 **Outer Western Carpathians, S Poland**

6 *Jolanta Pilch, Włodzimierz Margielewski, Renata Stachowicz-Rybka, Krzysztof*

7 *Buczek, Mateusz Stolarczyk, Łukasz Musielok, Katarzyna Korzeń, Dariusz Sala*

8

9

10

11 **Introduction**

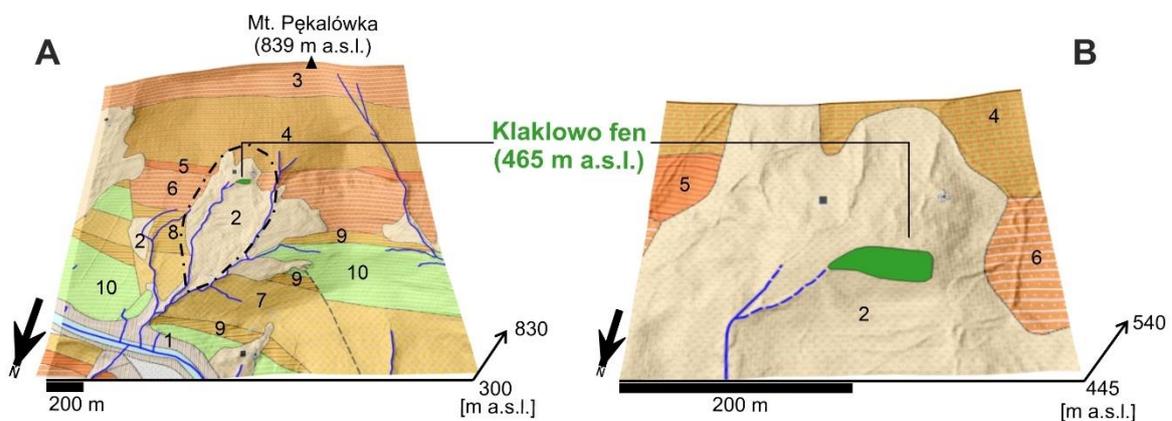
12

13 Study site – Klaklowo landslide geometry and geological description

14

15 The area of the Klaklowo landslide is covered mainly with forest in the upper part of
16 the hill, and with agricultural land at the foothill. Inhabited areas belong to the nearby
17 Stróża village. The Klaklowo landslide occupies an area which is 700 m long and 300
18 m wide, has an amphitheatre shape and its central point lies at 450 m a.s.l. (Fig. 1
19 D). Based on radiocarbon dating of organic sediments filling the numerous
20 depressions occurring within the landslide area it represents a type of multiple
21 rotational landslide which on the course of its development experienced several
22 rejuvenations (Margielewski 2001). The upper part of the landslide (ESM-Fig. 1 A and
23 B), comprising head scarp and sub-scarp depression (filled with deposits of the
24 Klaklowo fen) developed within flysch rocks of the Eocene age (Książkiewicz et al.
25 2016; Wójcik and Rączkowski 1994): shales, green shales and thin-bedded

26 sandstones of Hieroglyphic beds, variegated shales and thick-bedded sandstones
 27 and conglomerates and shales of Lower Pasierbiec Sandstones and Osielec
 28 Sandstones. The lower part of the Klaklowo landslide cuts through the Ciężkowice
 29 Sandstones (Eocene), variegated shales (Eocene, Palaeocene) and Inoceranian
 30 beds (sandstones and shales, Maastrichtian and Palaeocene). The uppermost zones
 31 of the mountain range, to which belongs Pękalówka Mt., are built of the sandstones
 32 of Magura beds.



33
 34 ESM-Fig. 1 – A) 3D view of DTM (digital terrain model,
 35 <https://mapy.geoportal.gov.pl/wss/service/PZGIK/NMT/GRID1/WCS/DigitalTerrainModelFormatTIFF>.) of the Klaklowo landslide zone (outline with dotted line) with the
 36 position of the Klaklowo landslide fen (area in green), draped with geological map
 37 (Książkiewicz et al. 2016,
 38 <https://cbdgmapi.pgi.gov.pl/arcgis/services/kartografia/smgp50k/MapServer/WMSServer>
 39 rver; see for explanation to numbers below); B) close-up on the DTM from ESM-Fig.
 40 2 A, showing Klaklowo landslide fen and its closest vicinity.
 41 Explanation to geological map – numbers correspond to geological units: 1 – Gravel,
 42 sands and clay of river terraces (erosion-accumulation and accumulation) 0.5–3.0 m
 43

44 above river level, Holocene; 2 – Clay, debris and blocks (blocks of flysh), colluvial,
45 Pleistocene and Holocene; Carpathian Flysch Rock of Magura Unit: 3 – Thick-
46 bedded sandstones and shales (glaucconitic facies), Magura beds, Eocene; 4 –
47 Shales, green shales and thin-bedded sandstones, Hieroglyphic beds, Eocene; 5 –
48 Variegated shales, Eocene; 6 – Thick-bedded sandstones and conglomerates and
49 shales (Lower Pasierbiec Sandstones and Osielec Sandstones), Eocene; 7 – Thick-
50 bedded sandstones and shales (Ciężkowice Sandstones), Eocene; 8 – Variegated
51 shales, Palaeocene and Eocene unseparated; 9 – Variegated shales, Palaeocene;
52 10 – Sandstones and shales, Inoceranian beds, Maastrichtian and Palaeocene;
53 black solid line – certain faults; black dotted line – presumable faults; black squares –
54 sites with deposits dated with radiocarbon method; flower symbol – sites with
55 deposits where palaeo-flora was found; black solid-dotted line – extent of Klakłowo
56 landslide.

57

58 **Materials and methods**

59

60 Sources of basemaps

61

62 Sources of basemaps used in Fig. 1 of the manuscript – part A)

63 <https://www.naturalearthdata.com/downloads/10m-cross-blend-hypso/cross-blended->

64 [hypso-with-relief-water-drains-and-ocean-bottom/](https://www.naturalearthdata.com/downloads/10m-cross-blend-hypso/cross-blended-hypso-with-relief-water-drains-and-ocean-bottom/)); part B) digital terrain model DTM

65 <https://download.gebco.net/> draped with the basemap of the part A); part C) DTM

66 from WCS service

67 [https://mapy.geoportal.gov.pl/wss/service/PZGIK/NMT/GRID1/WCS/DigitalTerrainMo-](https://mapy.geoportal.gov.pl/wss/service/PZGIK/NMT/GRID1/WCS/DigitalTerrainModelFormatTIFF.)

68 [delFormatTIFF.](https://mapy.geoportal.gov.pl/wss/service/PZGIK/NMT/GRID1/WCS/DigitalTerrainModelFormatTIFF.)). Maps A, B and C are projected in ETRS89 Lambert Conformal

69 Conic; latitude and longitude according to geographic coordinate reference system
70 ETRS89.

71

72 Geochemical determinations of Ca, Mg, K, Na, Fe, Mn, Ni, Cu, Zn, Pb

73

74 Samples were dried at 105 ± 5 °C in a vacuum dryer (Alpina EG40, Poland) for 24
75 hours and then placed in a muffle furnace to be ashed at a temperature of 600°C for
76 another 6 hours. Accurately weighted ca. 200 mg of the material was dissolved using
77 concentrated acids (HF and HNO₃) at 180°C in closed PTFE containers in the
78 microwave digestion system (PreeKem M6). After cooling, the samples were filtered
79 to avoid blocking of sample introduction system and diluted to the final volume
80 (50mL). An Agilent 8900 Triple Quadrupole ICP-MS (Agilent Technologies, USA)
81 instrument was used for the elemental determination (Ca, Mg, K, Na, Fe, Mn, Ni, Cu,
82 Zn, Pb) of geochemical analyses. The isobaric interferences were reduced using the
83 integrated collision/reaction cell in helium as the collision gas mode.

84

85 Pollen and non-pollen palynomorph (NPPs) analysis

86

87 Pollen identification was based on available keys (Moore et al. 1991; Reille 1992;
88 Beug 2004) and the reference collection of modern pollen slides. Non-pollen
89 palynomorphs were recognized on the basis of van Geel (1978) and van Geel et al.
90 (1980, 2003, 2007).

91

92 Macrofossil analysis

93

94 Plant macrofossil (fruits, seeds, needles, urticles, oospores and others) were
95 recognized according to appropriate atlases, keys and publications (Körber-Grohne
96 1964, 1991; Kats et al. 1965; Berggren 1969, 1981; Aalto 1970; Anderberg 1994;
97 Velichkevich and Zastawniak 2006, 2008; Mauquoy and van Geel 2007; Cappers et
98 al. 2012; Birks 2013; Kowalewski 2014) and compared with a reference collection of
99 modern diaspores as well as with specimens of fossil flora from the National
100 Biodiversity Collection of Recent and Fossil Organisms stored at W. Szafer Institute
101 of Botany PAS in Kraków (herbarium KRAM). Some animal remains (ephippia,
102 statoblasts, gemmules and others) were identified to the lowest possible rank (family
103 or genus) based on Mauquoy and van Geel (2007) and Kowalewski (2014). Botanical
104 nomenclature was adopted after (Mirek et al. 2020), whereas phytosociological
105 nomenclature after Matuszkiewicz (2017). Local palaeoecological interpretation of
106 identified taxa was mostly based on Zarzycki (2002) and other cited sources.

107

108 **Results**

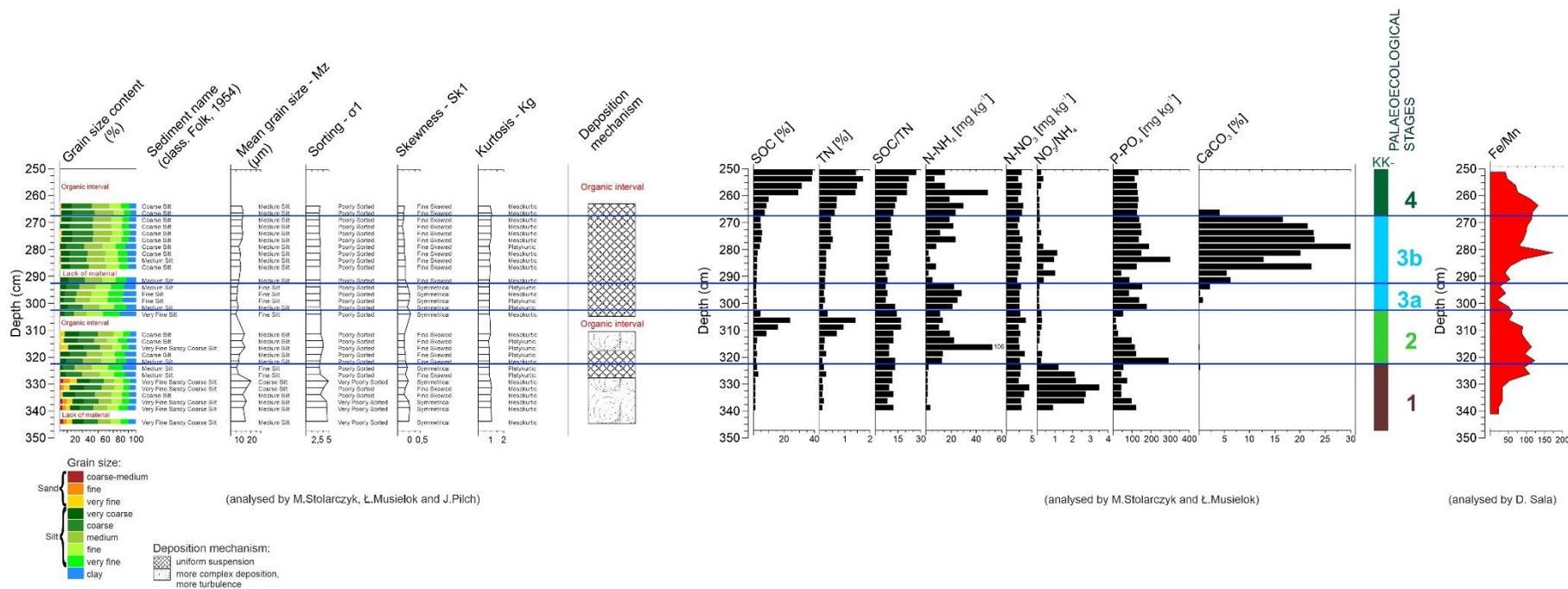
109

110 Grain-size analysis – detailed description of sediment type along the profile and Folk
111 and Ward (1957) parameters

112

113 Sediment in the lower part of the stage KK-1 (ESM-Fig. 2) is composed of coarse silt
114 with an admixture of very fine sand, poorly and very poorly sorted. In the upper part
115 sediment is poorly sorted and exhibits finer grain size (medium silt) devoid of sandy
116 component. It is also expressed as a slight but noticeable drop in Mz (from coarse to
117 fine silt). In the lowest part of stage KK-2 sedimentation of poorly sorted medium silt
118 still prevails. Upward the sediment profile, an addition of very fine sand occurs,

119 whereas silt becomes coarser. In stage KK-3a sedimentation of silt fine- and
120 medium-grained poorly sorted silt took place. It is also expressed as a slight but
121 noticeable drop in M_z (from medium to fine silt). Stage KK-3b is dominated by
122 sedimentation of poorly sorted coarse silt with trace amount of sand fraction. In stage
123 KK-4 moss fen peat accumulation starts. Among parameters of Folk and Ward
124 (1957), mean grain size (M_z) varies between 5.20 and 20.09 μm , what corresponds
125 to silt according to classification based on Udden (1914) and Wentworth (1922).
126 Standard deviation (σ_1) of grain size, expressing the degree of sorting, show values
127 2.81–4.89 what implies mostly the poorly sorted, and at some depth very poorly
128 sorted material. Skewness (Sk_1) values range from -0.3 to 0.1 what corresponds to
129 fine skewed and symmetrical distribution of the grain size in samples. Values of
130 kurtosis (K_g) vary from 0.85 to 1.06 pointing at platykurtic and mesokurtic data
131 distribution.



132

133 ESM-Fig. 2 – Sediment grain-size and geochemical data of the depth section 250–350 cm of the Klaklwo landslide fen deposits.

134 Grain size content: a determine percentage of particles of each size fraction according to modified scale from Udden (1914) and

135 Wentworth (1922) with a physical description of the textural group of the sample and the sediment type according to Folk (1954);

136 Folk and Ward (1957) parameters (graphical method using linear interpolation): mean grain size (Mz), standard deviation (σ_1),

137 skewness (Sk1) and kurtosis (Kg); deposition mechanism according to C-M diagram (ESM-Fig. 3). See main text for explanation of

138 zonation.

- 139 Pollen analysis – detailed description of pollen zones
- 140
- 141 Pollen zones description divided into 5 palaeoecological stages of the Klaklowo
- 142 landslide fen development is given in ESM-Table 1.

143 **ESM-Table 1** Results of pollen analysis divided into 5 palaeoecological stages of the Klaklowo landslide fen development (see
 144 pollen diagram in Fig. 4)

Palaeoecological stage of the Klaklowo fen development	Description of pollen zones
Stage KK-1 (ca. 14,040– >14,790 mod. cal yrs BP, ca. >750 mod. years): Development of the waterbody I after formation of the Klaklowo landslide and sub-scarp depression	The entire pollen zone P1 (depth interval: 332.5–367.0 cm) is comprised within stage KK-1. It is entirely devoid of pollen grains.
Stage KK-2 (ca. 13,870–14,040 mod. cal yrs BP, ca. 170 mod. years): Basin drainage and formation of a short-lasting fen	Stage KK-2 corresponds to the lower part of the pollen zone P2 (287.5–332.5 cm), which is poor in pollen and rather not interpretable. The number of pollen grains reaches the “highest” values for the horizon of decomposed peat at 315.0–322.5 cm (Fig. 4). The slight increase in <i>Pinus sylvestris</i> and <i>Betula</i> (undiff.) pollen occurs here, as well as there is a noticeable presence of Poaceae and <i>Artemisia</i> pollen. There is also some trace amount of pollen from <i>Corylus avellana</i> , <i>Quercus</i> and <i>Picea abies</i> . Among spore plants <i>Equisetum</i> pollen make a distinctive part. In some parts of this zone corroded grains constitute almost half of the entire amount of pollen.
Stage KK-3a (13,790–13,870 mod. cal yrs BP, ca. 80 mod. years): Colonization of waterbody II	Stage KK-3a (295.0–307.5 cm) corresponds to the upper part of the pollen zone P2 (287.5–332.5 cm), which is poor in pollen and rather not interpretable.
Stage KK-3b (13,620–13,790 mod. cal yrs BP, ca. 170 mod. years): Waterbody II overgrowing	Stage KK-3b corresponds to the lower part of interpretable pollen zone P3 (600–700 pollen grains). Within the depth range of clastic sedimentation (267.5–287.5 cm, Fig. 4) it is characterized by predominance of AP vs NAP vegetation, with highest percentage of <i>Pinus sylvestris</i> (ca. 40–80%), <i>Betula</i> undiff. (ca. 25–40%), presence of <i>Salix</i> undiff. up to 5%, and occurrence of thermophilous plant taxa: a distinct share of <i>Corylus avellana</i> (up to 5%) and trace amounts of <i>Quercus</i> , <i>Carpinus betulus</i> and <i>Ulmus</i> . Admixture of <i>Fagus sylvatica</i> and <i>Abies alba</i> is also noticeable. Among the herbs group Poaceae, Cyperaceae and <i>Artemisia</i> pollen prevails (up to 5%). From NPPs mainly <i>Pediastrum</i> , <i>Arcella</i>

arenaria/catinus and *Endophlyctis lobata* T13 were identified. Number of corroded pollen grain (up to 200) is also distinctive.

Stage KK-4 (<13,530–13,620 mod. cal yrs BP, ca. >90 mod. years):
Waterbody II transition to a long-lasting fen

Stage KK-4 corresponds to the upper part of the interpretable pollen zone P3 (600–700 pollen grains). In the depth range of 250.0–267.5 cm (Fig. 4), the beginning of peat accumulation coincides with a slight increase of share of *Betula* pollen and its further decline. On the contrary, share of *Pinus sylvestris* pollen slightly declines to 40% and rises to 80% from depth 265 cm. Most herb taxa (Cyperaceae, Poaceae and *Artemisia*) also show an initial decrease and further rise. Also, some new NPPs taxa are present in this interval.

- 146 Macrofossil analysis – detailed description of LMAZ
- 147
- 148 Detailed LMAZ description and interpretation divided into 5 palaeoecological stages
- 149 of the Klaklowo landslide fen development is given in ESM-Table 2.

150 **ESM-Table 2** Results of the macrofossil analysis divided into 11 LMAZ and 5 palaeoecological stages of the Klaklowo landslide fen
 151 development).

LMAZ	Results of plant macrofossil analysis	Macrofossil-based local palaeoecological interpretation
Stage KK-1 (330–367 cm, ca. 14,040– >14,790 mod. cal yrs BP, ca. >750 mod. years): Development of the waterbody I after formation of the Klaklowo landslide and sub-scarp depression		
M1 (357.5– 367.0 cm)	Fragments of needles of <i>Larix decidua</i> ; small but noticeable number of <i>Juncus</i> sp. seeds; single remain of <i>Typha</i> sp. fruit and trace amounts of Bryopsida mosses; some amounts of oospores of aquatic Characeae; a few sclerotia of <i>Cenococcum geophilum</i> and Ostracoda; abundant charcoal fragments.	Few macroremains indicate that cold climate, oligotrophic, open-space conditions with only single tree stands (<i>Larix decidua</i>) and moist/wet or aquatic habitat (<i>Juncus</i> sp. seeds, Characeae oospores, Ostracoda) probably prevailed in the Klaklowo basin after its formation. Judging by a great number of charcoal fragments, intense palaeo-fires seem to take place in the basin surrounding during that time.
M2 (350.0– 357.5 cm)	Some fragments of <i>Larix decidua</i> needles; single fruits of birch shrubs (<i>Betula humilis</i> , <i>Betula nana</i>); an increasing number of <i>Juncus</i> sp. seeds; a single seed of <i>Parnassia palustris</i> ; small amounts of Bryopsida mosses; single fruit of biconvex <i>Carex</i> sp.; a trace, but continuous occurrence of Characeae oospores. Charcoal fragments sharply disappear in this zone, animal remains drops to trace quantities.	The occurrence of the first organic horizon, which intercalates the minerogenic sequence, signalizes that local environment became definitely more boggy at that time. The plant taxa are more abundant and diverse here, dominated by <i>Juncus</i> sp. and Bryopsida mosses, what can reflect the process of waterbody shallowing and vegetation encroachment. Some representatives of <i>Larix decidua</i> and <i>Betula humilis</i> could occur as tree-shrub patches in the surrounding steppe-tundra.
M3 (347.5– 350.0 cm)	Trace amounts of larch needle fragments and <i>Betula humilis</i> fruits; single seeds of <i>Dianthus</i> sp.; several Poaceae fruits and single seeds of <i>Juncus</i> sp.; a fruit of <i>Valeriana simplicifolia</i> ; several Bryopsida mosses stems; a few sclerotia of <i>Cenococcum geophilum</i> ; a noticeable number of Oribatid mites. Charcoal fragments suddenly reappear in significant amount.	Although similar in plant taxa composition to M2, this LMAZ was distinguished due to appearance of a high number of Poaceae fruits, withdrawal of <i>Juncus</i> sp., appearance of macroremains of <i>Dianthus</i> sp. and <i>Valeriana simplicifolia</i> and re-appearance of abundant charcoal fragments. This noticeable change in phytocenosis in the developed short-lasting fen could be related to some drainage and desiccation event at the M2 and M3 boundary.
M4 (330.0– 347.5 cm)	Interval is quite thick comparing to the other subzones, but a number of plant macrofossils is rather small: some fragments of <i>Pinus sylvestris</i> needles in the bottom part; single seeds of <i>Dianthus glacialis</i> , <i>Arabis alpina</i> and Poaceae. In the top part: fruits and seeds	In a thick interval of medium silt of the LMAZ M4 the local conditions seem to be cold, aquatic and poor in vegetation, what is confirmed by occasionally identified macrofossils of <i>Juncus</i> sp. and <i>Scirpus sylvaticus</i> (moist-wet habitat) or Characeae, <i>Batrachium</i> sp. and <i>Zannichellia</i>

	of <i>Scirpus sylvaticus</i> ; Bryopsida mosses present in trace amounts; fruits of <i>Batrachium</i> sp. and <i>Zannichelia palustris</i> ; a disappearance of Characeae oospores. From the middle part of this interval the amount of <i>Cenococcum geophilum</i> sclerotia starts increasing upward. Also: a single occurrence of Ostracoda and <i>Daphnia</i> sp.; animal remains appear in rather small number.	<i>palustris</i> (aquatic habitat). Remnants of plant taxa specific for drier habitats (Poaceae) and related to low temperatures (<i>Dianthus glacialis</i> , <i>Arabis alpina</i>) were probably transported to the basin from the surrounding area.
Stage KK-2 (307.5–330.0 cm, ca. 13,870–14,040 mod. cal yrs BP, ca. 170 mod. years): Basin drainage and formation of a short-lasting fen		
M5 (322.5–330.0 cm)	Scarce quantities of <i>Larix decidua</i> needle fragments; some <i>Poaceae</i> fruits and <i>Juncus</i> sp. seeds; numerous fruits of <i>Scirpus sylvaticus</i> ; a single <i>Eleocharis palustris</i> fruit; numerous sclerotia of <i>Cenococcum geophilum</i> .	Judging by the numerous sclerotia of <i>Cenococcum geophilum</i> the intensified redeposition of material from the vegetation-depleted surrounding to the basin centre probably took place in this zone. The onset of the fen development is signaled by the presence of Characeae oospores (aquatic conditions) as well as by macrofossils of eulittoral zone taxa: <i>Juncus</i> sp., <i>Scirpus sylvaticus</i> and <i>Eleocharis palustris</i> (growing <i>in situ</i> or re-redeposited).
M6 (315.0–322.5 cm)	Zone rich in different plant taxa: a few <i>Pinus sylvestris</i> macrofossils; a single occurrence of <i>Betula humilis</i> fruit; <i>Larix decidua</i> fragments present in small amount; a noticeable amount of Poaceae fruits; some new-coming species: single fruits of <i>Dryas octopetala</i> and <i>Poa</i> cf. <i>alpina</i> , single seed of <i>Androsace</i> cf. <i>chamaejasme.</i> , <i>Melandrium rubrum</i> , <i>Epilobum</i> cf. <i>parviflorum</i> and <i>Parnassia palustris</i> . Also: reappearance of some fruits of <i>Valeriana simplicifolia</i> and a large increase in number of <i>Eleocharis palustris</i> fruits; for the first-time appearance of a large number of <i>Carex rostrata</i> and minor quantity of <i>Carex diandra</i> macrofossils; a spindle of <i>Eriophorum vaginatum</i> ; some fruits of <i>Phragmites australis</i> . The occurrence of Bryopsida mosses was impossible to determine due to a high degree of decomposition of plant remnants. Moreover: a noticeable rise in a number of Characeae oospores; a noticeable presence of Ostracoda, Oribatid mites and larval cases of Trichoptera; abundant sclerotia of <i>Cenococcum geophilum</i> ceasing toward the subzone top; in the topmost sample short reappearance of abundant charcoal fragments.	This LMAZ records the further vegetation encroachment at more advanced stage of fen development what is reflected in the dominating occurrence of the boggy taxa: <i>Valeriana simplicifolia</i> , <i>Carex rostrata</i> , <i>Carex diandra</i> , <i>Eleocharis palustris</i> and <i>Phragmites australis</i> , suggesting water depth less than 1 m with the interannual fluctuations of 1 m (Gaillard and Birks 2007) and perhaps some pools with standing water (Characeae). The establishment of alliances <i>Magnocaricion</i> Koch 1926 and <i>Phragmition</i> Koch 1926 was probable, whereas trophy was mostly medium, locally even low (<i>Eriophorum vaginatum</i>). Along with Poaceae, the newcoming heliophilous taxa: <i>Dryas octopetala</i> , <i>Poa</i> cf. <i>alpina</i> , <i>Androsace</i> cf. <i>chamaejasme</i> imply an open-space and dry/fresh habitat existing in the fen surrounding. Presently, these plant taxa are typical for mountain and upland alpine meadow grass, therefore it can be concluded that a cold steppe-tundra conditions (with some single stands of Scots pine, larch and shrubby birch) could prevail in the region of the Beskid Makowski Mountains. Furthermore, <i>Androsace</i> cf.

		<i>chamaejasme</i> and <i>Dryas octopetala</i> are indicators of calcareous substrate.
M7 (307.5–315.0 cm)	It is distinguished due to occurrence of well-preserved and quite numerous fragments of Bryopsida mosses occurring along with some <i>Carex</i> sp. and <i>Scirpus sylvaticus</i> macrofossils. Moreover: some sporangia of <i>Thelypteris palustris</i> and fruits of <i>Urtica dioica</i> ; a single fruits of <i>Betula nana</i> and <i>Betula</i> sp.; single macrofossils of Lamiaceae, Poaceae and <i>Juncus</i> sp.; several Characeae oospores; a further increase in a number of Ostracoda; rising occurrence of <i>Daphnia</i> sp.; first appearance of <i>Ceriodaphnia</i> sp. and Chironomidae in minor amount in the topmost sample.	LMAZ KK-M7 seems to be a continuation of a boggy habitat (constant presence of <i>Carex</i> sp. and reappearance of <i>Scirpus sylvaticus</i>), however, the number of taxa from dry to boggy ecological groups is noticeably reduced. Furthermore, the well-preserved and quite numerous fragments of Bryopsida mosses are contrastive to highly decomposed organic remnants from KK-M6, probably suggesting some drainage event and rotting of the exposed soil. The first symptoms of the transition to fully aquatic conditions are recorded (abundant presence of Ostracoda and ehippia of <i>Daphnia</i> sp., also <i>Ceriodaphnia</i> sp. in the topmost sample), perhaps with some more nutrient-rich supply by groundwater, as it is indicated by the presence of eutrophic <i>Urtica dioica</i> and <i>Thelypteris palustris</i> .
Stage KK-3a (295.0–307.5 cm, 13,790–13,870 mod. cal yrs BP, ca. 80 mod. years): Colonization of waterbody II		
M8 (295.0–307.5 cm)	A noticeable number of fragments of <i>Larix decidua</i> needles; few macrofossils of <i>Pinus sylvestris</i> and <i>Betula</i> sp.; minor number of fruits of <i>Carex</i> sp. and <i>Scirpus sylvaticus</i> ; Bryopsida mosses again less common. Moreover: a great increase in a number of Characeae oospores (from tens to almost nine hundreds) in the uppermost sample; first appearance of fruits of <i>Batrachium</i> sp. and fragments of endocarps of <i>Potamogeton</i> sp.; a rising trend in a number of ostracods and <i>Daphnia</i> sp. ehippia; small or trace amounts of <i>Simocephalus</i> sp. ehippia; Porifera gemmules; <i>Plumatella</i> statoblasts; Chironomidae remnants.	A great increase in a number of macrofossils of aquatic plant and animal taxa (abundant Characeae oospores, the first appearance of <i>Batrachium</i> sp. and <i>Potamogeton</i> sp., a rising number of ostracods and <i>Daphnia</i> sp. ehippia, <i>Simocephalus</i> sp. ehippia, Porifera gemmules, <i>Plumatella</i> statoblasts, as well as Chironomidae remains) documents development of the Klaklowo waterbody II and its subsequent colonization by plants. Palaeo-pond probably possessed a (eulittoral) zone with boggy plant taxa (<i>Carex</i> sp. and <i>Scirpus sylvaticus</i> but with Bryopsida mosses withdrawal) and was surrounded by some tree patches of <i>Larix decidua</i> , <i>Pinus sylvestris</i> and <i>Betula</i> sp.
Stage KK-3b (267.5–295.0 cm, 13,620–13,790 mod. cal yrs BP, ca. 170 mod. years): Waterbody II overgrowing		
M9 (267.5–295.0 cm)	It is characterized by the greatest number of plant and animal taxa which show high abundances and very consistent trends: a number of macrofossils of <i>Betula</i> sect. <i>Albae</i> and <i>Betula</i> sect. <i>Nanae</i> growing with decreasing depth (from the middle part of this LMAZ upward the	LMAZ KK-M9 is the most abundant in macrofossils of both plant and animal origin comparing to the other LMAZ units. The constant occurrence of representatives of aquatic plants indicates the permanent existence of the Klaklowo waterbody II. Moreover, the very consistent

	<p>profile a great increase in shares of <i>Betula nana</i> and <i>Betula pubescens</i>). Moreover: a continuous presence of Conifere bud scales; scarce occurrences of <i>Dryas octopetala</i>, <i>Asteraceae</i>, <i>Thalictrum</i> sp. and some minor amounts of Poaceae; growing and later decreasing trend in a number of fruits and urticles of <i>Carex rostrata</i> and in a lesser degree of <i>Carex diandra</i>; number of Bryopsida mosses macro-remains significantly growing upward the interval; single appearance of <i>Rumex hydrolapathum</i> fruit.</p> <p>Among aquatic taxa there are abundant Characeae oospores, quickly growing from the lowermost samples and soon reaching the highest number (>2000 oospores) which is maintained until the end of the interval. Moreover: a gradual growth and later a gradual decrease (toward the upper limit of the zone) in a number of <i>Batrachium</i> sp. fruits synchronously with the occurrence of fragments of endocarps of <i>Potamogeton</i> sp; irregularly present single endocarps of <i>Potamogeton pusillus</i> along with fruits of <i>Myriophyllum verticillatum</i> and <i>Hippuris vulgaris</i>; a growing trend (and in some cases later also decreasing) in a number of animal macro-remains: Ostracoda, <i>Daphnia</i> sp., <i>Simocephalus</i> sp., Porifera, <i>Plumatella</i> sp., Oribatid mites and Chironomidae.</p>	<p>trends of changes in abundance of the occurring taxa (among plants: Characeae oospores and <i>Batrachium</i> sp. fruits, among animal macrofossils: Ostracoda, <i>Daphnia</i> sp., Chironomidae), document the progress of aquatic plant succession of the Klaklowo palaeo-pond II. Concentration of Characeae oospores exceeds approximately 5 times the documented concentration (more than 100 oospores/100 cm³) characteristic for the <i>in situ</i> occurrence of Characeae plant communities (Szymczyk 2015 and references therein), what suggest that the vast submerged Characeae meadows, class <i>Charetea</i> (Fukarek 1961 n.n.) Krausch 1964, spread at the bottom of the waterbody. Their presence confirms that the water conditions were well-transparent and oligo- to mesotrophic. The continuous presence of the macrofossils of <i>Batrachium</i> sp. and <i>Potamogeton</i> sp. along with the changing presence of <i>Myriophyllum spicatum</i>, <i>Hippuris vulgaris</i> and <i>Potamogeton pusillus</i>, being typical of the alliance <i>Potamion</i> Koch 1926 em. Oberd. 1957, suggests that these taxa could occur in a form of single patches among Charophyte meadows. A growing number of macrofossils of <i>Betula nana</i>, <i>Betula pubescens</i>, <i>Carex rostrata</i>, <i>Carex diandra</i> and Bryopsida mosses signalize the terrestrial plants succession (birch boreal forest) and together with representatives of <i>Potamion</i> plant community, contributed to the waterbody overgrowing. Taxa of dry, fresh and moist habitats, apart from a single occurrence of <i>Dryas octopetala</i>, <i>Asteraceae</i> and some minor amounts of Poaceae, were not recorded in this zone.</p>
<p>Stage KK-4 (250.0–267.5 cm, <13,530–13,620 mod. cal yrs BP, ca. >90 mod. years): Waterbody II transition to a long-lasting fen</p>		
<p>M10 (260.0–267.5 cm)</p>	<p>Remains of trees and shrubs of this LMAZ are the most abundant for the entire 250-367 cm depth section: there are tens of fruits and fruit scales of <i>Betula nana</i>, <i>Betula pubescens</i> and <i>Betula</i> sp. predominating at the bottom boundary of this zone and further declining to the LMAZ top. Moreover: first appearance of large amount of <i>Pinus sylvestris</i> needles rising upward to the subzone's top; presence of <i>Larix decidua</i></p>	<p>It can be concluded that in the catchment of the Klaklowo palaeo-pond II swampy forest dominated by <i>Pinus sylvestris</i> started developing at that time, probably outcompeting <i>Betula nana</i> and <i>Betula pubescens</i> which tolerate rather only moderate shade. Locally, the reservoir could be heavily overgrown with <i>Carex rostrata</i>, <i>Carex diandra</i> and Bryopsida mosses, what also could cause retreat of aquatic plants and animals.</p>

	macrofossils in minor amounts; high quantities of <i>Carex rostrata</i> and <i>Carex diandra</i> macrofossils rising throughout this interval; high number of Bryopsida mosses macro-remains; a sharp decline in number of Characeae oospores from >2000, through 350, to ca. 20–40 within a 5 cm depth interval; a disappearance of fruits of <i>Batrachium</i> sp. and <i>Potamogeton</i> sp.; a continuing presence of <i>Hippuris vulgaris</i> ; decline and/or disappearance of animal remains.	
M11 (250– 260 cm)	A further declining trend in a number of <i>Betula nana</i> and <i>Betula pubescens</i> macrofossils; after the initial drop, a rising trend in a number of <i>Pinus sylvestris</i> needles; a noticeable decrease in a number of <i>Carex diandra</i> fruit and urticles; an initial rise of <i>Carex rostrata</i> and its further ceasing; a sharp reduction in a number of Bryopsida mosses remnants; appearance of small amounts of fruits of <i>Glyceria maxima</i> , absence of remains of all aquatic and animal taxa except for Oribatid mites, which further starts to decrease in number.	Both LMAZ M10 and M11 document a transition from Klaklowo palaeo-pond II into a long-lasting Klaklowo fen. The ultimate disappearance of aquatic plants and animals reflects that the conditions for their survival were no longer favourable, but it cannot be excluded that some larger pools with stagnant water persisted. The fen was certainly water-logged and meso-/eutrophic, however in the zone M11 also sedges and Bryopsida mosses are gradually diminishing in number.

153 **Additional interpretation**

154

155 Grain-size analysis – C-M diagram

156

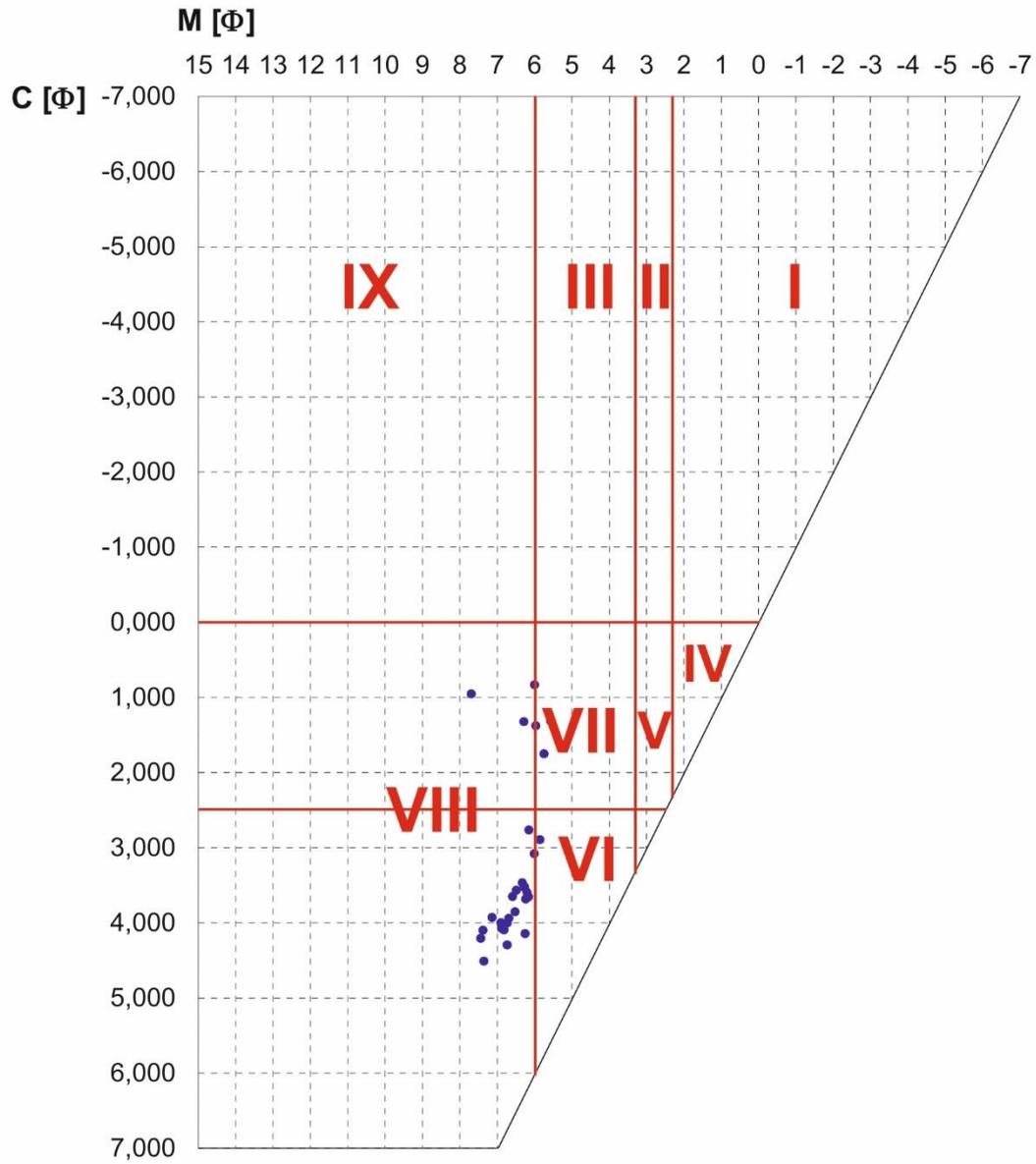
157 According to C-M diagram (ESM-Fig. 3), more than 80% of the analysed samples
158 were placed in the VIII area of the diagram that implies the finest uniform suspension
159 as a deposition mechanism – the sediment was settled from the deposition of
160 particles and was not sorted by bottom current (Passega and Byramjee 1969).

161 Among remaining samples, several of the bottommost depth interval (327.5-345.0
162 cm) lied in or close to the VII area which corresponds to deposition mechanism by
163 uniform suspension with more complex deposition. Another 2 samples (310.0-312.5
164 and 315.0-317.5) were placed in the VI area which is related to graded suspension
165 transported in low turbulent conditions. It must be stressed, however, that the C-M
166 diagram is not sufficient to make a clear distinction between VI and VII type of
167 deposition mechanism (Passega and Byramjee 1969). In general, all the samples lied
168 in some proximity to the area VI-VII pointing that some influence from the bottom
169 currents occurred.

170

C/M Diagram

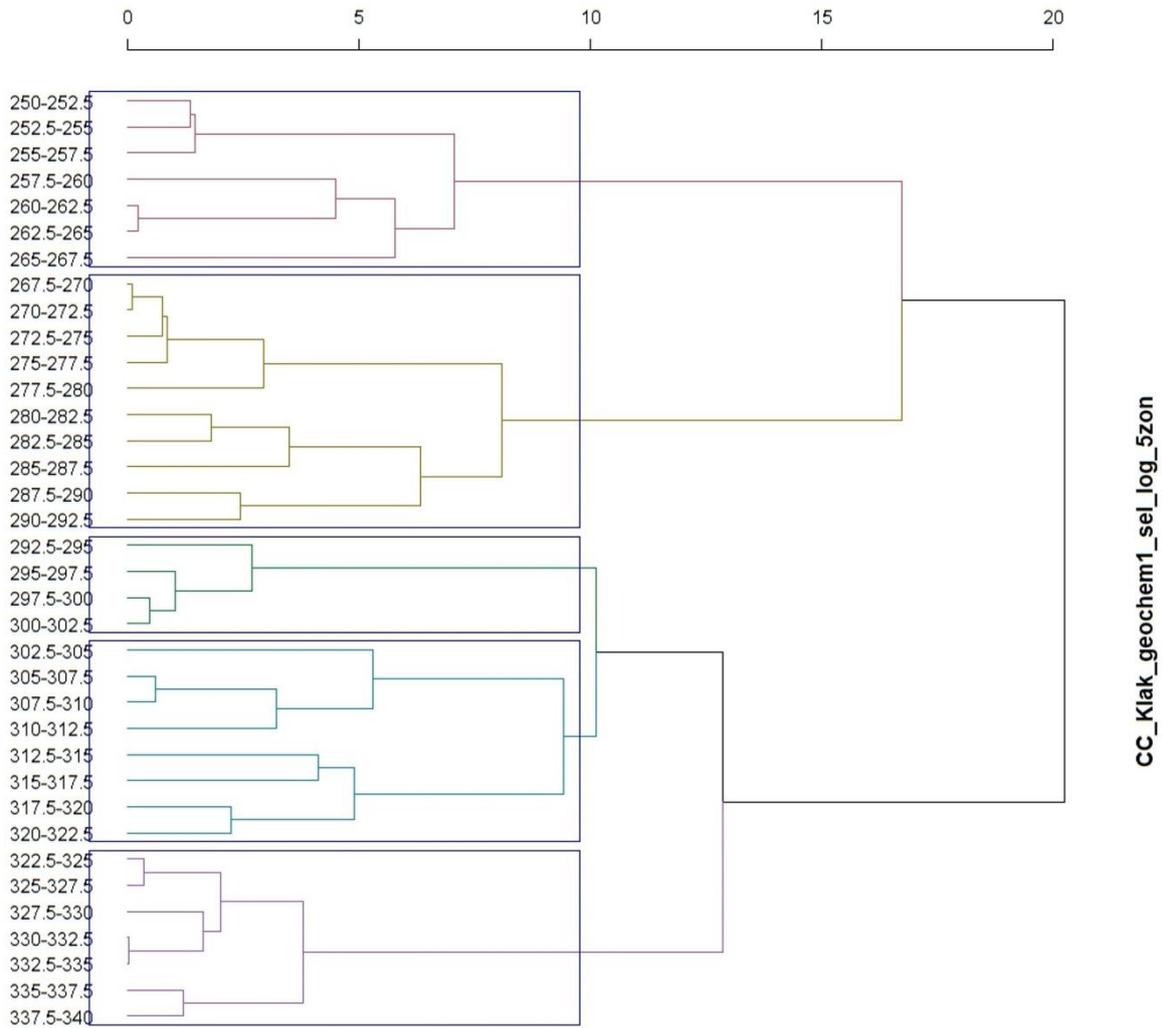
(Passega and Byramjee 1969)



Proportion of sediment samples in the diagram fields (conditions of sedimentation)[%]

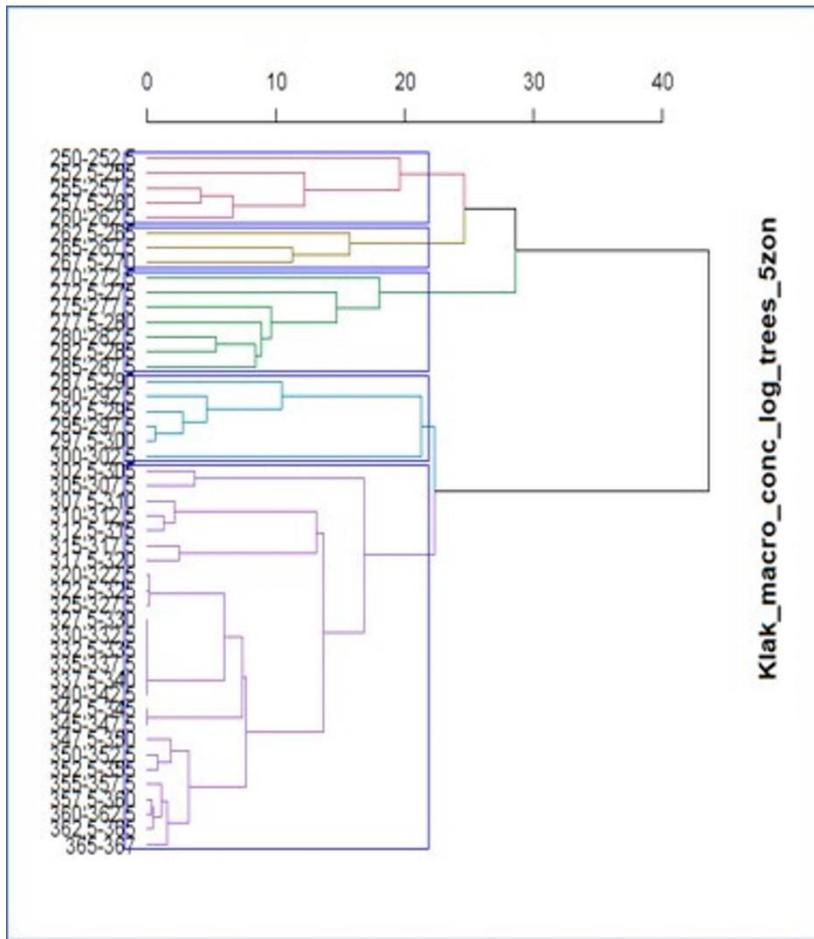
I: 0,00	IV: 0,00
II: 0,00	V: 0,00
III: 0,00	VI, VII: 17,24
IX: 0,00	VIII: 82,76

172 ESM-Fig. 3 – Klaklowo grain-size analysis results (samples) on C-M diagram, where
173 C – the one-percentile and M – the median of the grain-size distribution (Passega
174 and Byramjee 1969). Fields in the diagram correspond to conditions of
175 sedimentation: I, II, III, IX – dominant deposition by traction with small share of
176 suspension; IV – graded suspension transported in highly turbulent conditions; V –
177 graded suspension transported in moderately turbulent conditions; VI, VII – graded
178 suspension transported in low turbulent conditions, uniform suspension with more
179 complex deposition, respectively; VIII – finest uniform suspension and pelagic
180 suspension.



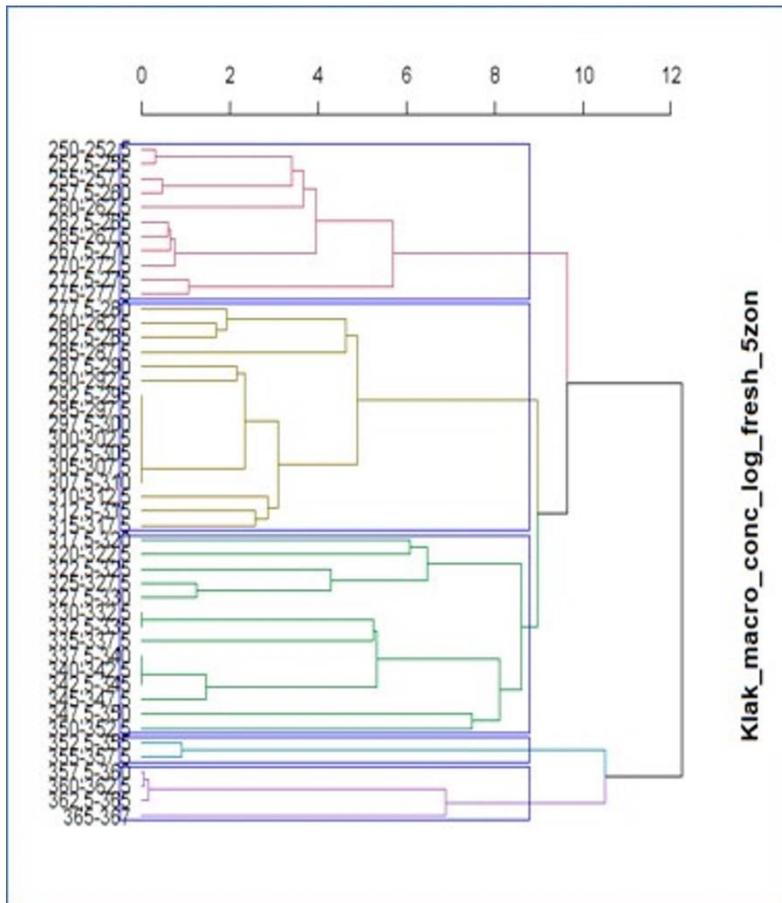
182

183 ESM-Fig. 4 – CONISS dendrogram based on selected geochemical variables: SOC,
 184 TN, N-NH₄, N-NO₃, P-PO₄, CaCO₃. Vertical axis: sample depth, horizontal axis: total
 185 dispersion. Rectangles and differentiated colours of branches refer to five zones
 186 suggested by broken stick model.



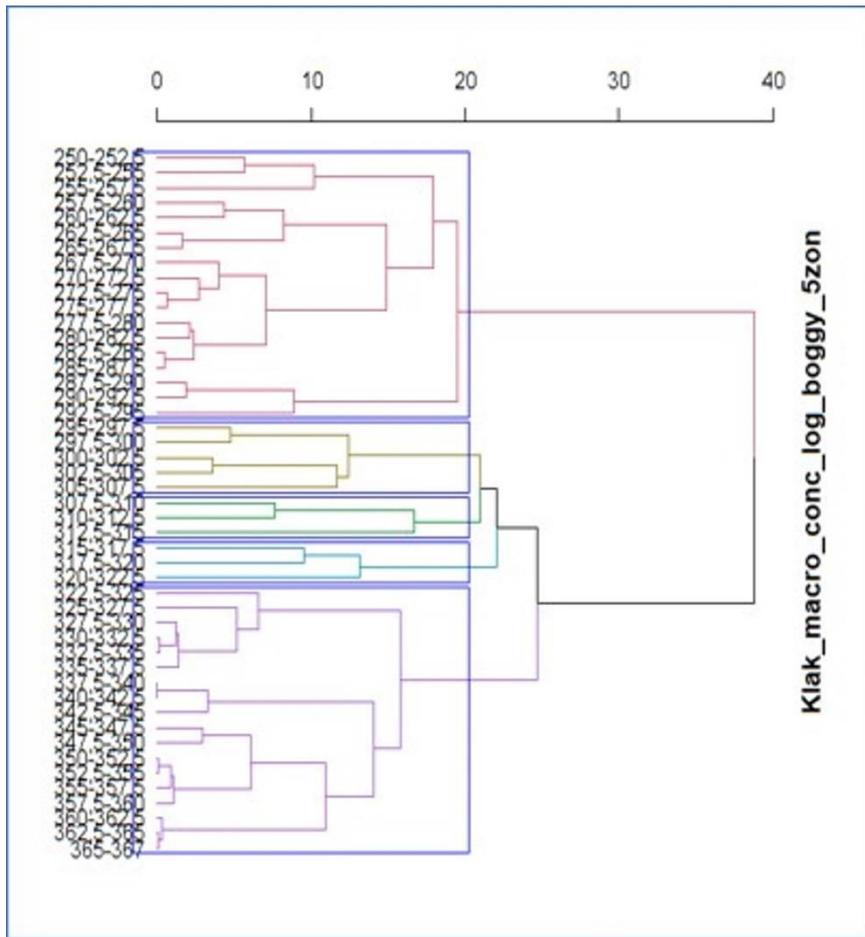
187

188 ESM-Fig. 5a – CONISS dendrogram based on selected plant macrofossil data –
 189 trees and shrubs habitats. Vertical axis: sample depth, horizontal axis: total
 190 dispersion. Rectangles and differentiated colours of branches refer to five zones
 191 suggested by broken stick model. Dendrogram was used for compilation of final
 192 macrofossil zonation together with other dendrograms.



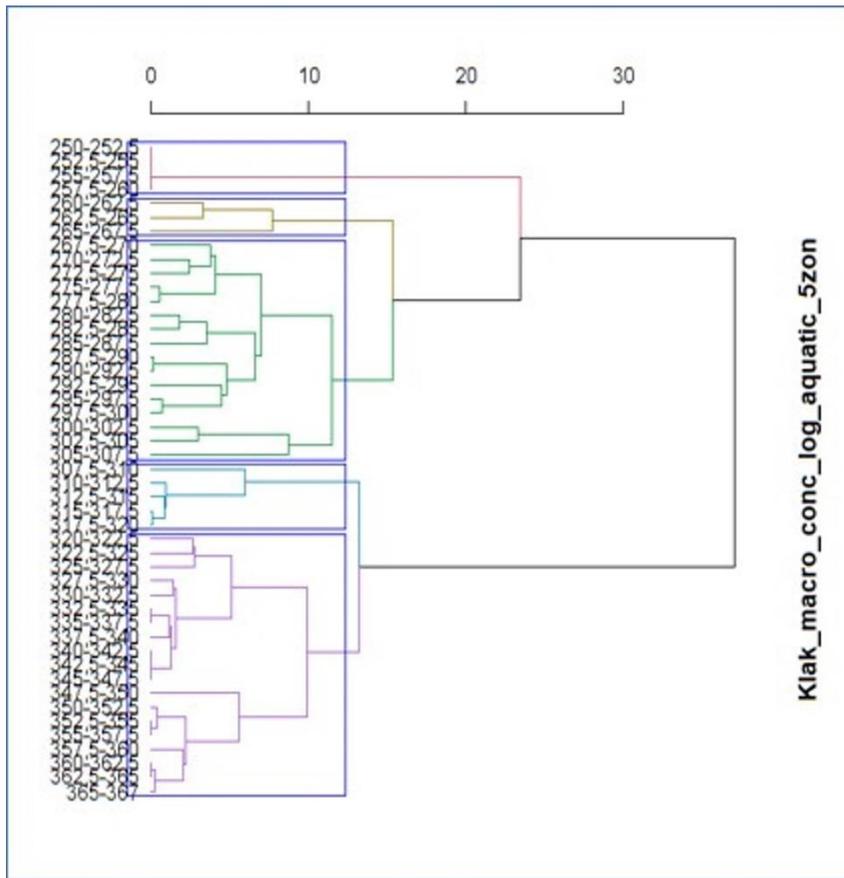
193

194 ESM-Fig. 5b – CONISS dendrogram based on selected plant macrofossil data – dry,
 195 fresh and moist habitats. Vertical axis: sample depth, horizontal axis: total dispersion.
 196 Rectangles and differentiated colours of branches refer to five zones suggested by
 197 broken stick model. Dendrogram was used for compilation of final macrofossil
 198 zonation together with other dendrograms.



199

200 ESM-Fig. 5c – CONISS dendrogram based on selected plant macrofossil – boggy
 201 and reedswamp habitats. Vertical axis: sample depth, horizontal axis: total
 202 dispersion. Rectangles and differentiated colours of branches refer to five zones
 203 suggested by broken stick model. Dendrogram was used for compilation of final
 204 macrofossil zonation together with other dendrograms.



205

206

207 ESM-Fig. 5d – CONISS dendrogram based on selected plant macrofossil data –

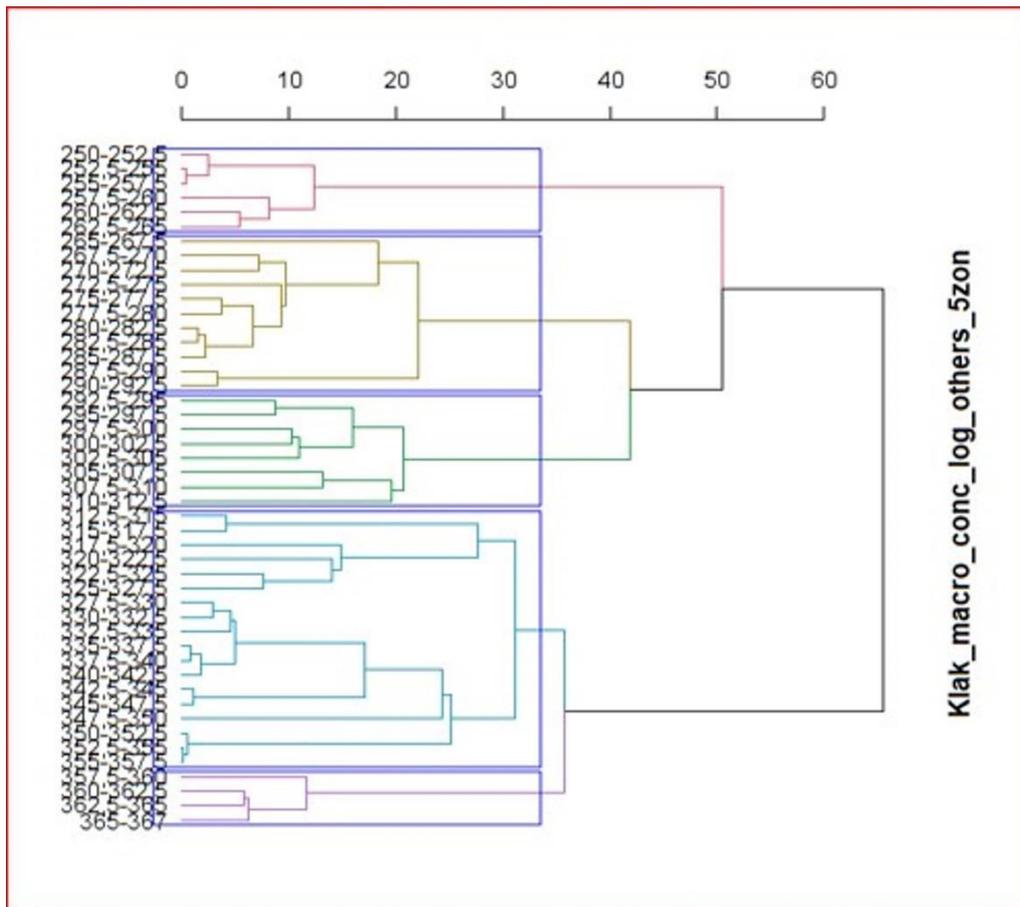
208 aquatic habitats. Vertical axis: sample depth, horizontal axis: total dispersion.

209 Rectangles and differentiated colours of branches refer to five zones suggested by

210 broken stick model. Dendrogram was used for compilation of final macrofossil

211 zonation together with other dendrograms.

212



213

214

215 ESM-Fig. 5e – CONISS dendrogram based on selected plant macrofossil data– other
216 types of macrofossils. Vertical axis: sample depth, horizontal axis: total dispersion.
217 Rectangles and differentiated colours of branches refer to five zones suggested by
218 broken stick model. Dendrogram was used for compilation of final macrofossil
219 zonation together with other dendrograms.

220 **References used in the Electronic Supplementary Material Text**

- 221
- 222 Aalto M (1970) Potamogetonaceae fruits I. Recent and subfossil endocarps of the
223 Fennoscandian species. *Acta Bot Fenn* 88:1–85
- 224 Anderberg A-L (1994) Atlas of seeds and small fruits of Northwest-European plant
225 species with morphological descriptions. Part 4. Resedaceae–Umbelliferae.
226 Swedish Museum of Natural History, Stockholm
- 227 Berggren G (1969) Atlas of seeds and small fruits of Northwest-European plant
228 species with morphological descriptions. Part 2: Cyperaceae. Swedish Natural
229 Science Research Council, Stockholm
- 230 Berggren G (1981) Atlas of seeds and small fruits of Northwest-European plant
231 species with morphological descriptions. Part 3: Salicaceae - Cruciferae.
232 Swedish Museum of Natural History, Stockholm
- 233 Beug HJ (2004) Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende
234 Gebiete. Verlag Dr. Friedrich Pfeil, München (in German)
- 235 Birks HH (2013) Plant macrofossil introduction. In: Elias SA, Mock CJ (eds)
236 *Encyclopedia of Quaternary Science*, Second Edi. Elsevier, Amsterdam, pp 593–
237 612
- 238 Cappers RTJ, Bekker RM, Jans JEA (2012) Digital seed atlas of the Netherlands/
239 Digitale Zadenatlas van Nederland, 2nd ed. Barkhuis Publishing & Groningen
240 University Library, Groningen
- 241 Folk RL (1954) The distinction between grain size and mineral composition in
242 sedimentary-rock nomenclature. *J Geol* 62:344–359
- 243 Folk RL, Ward WC (1957) Brazos River bar: a study in the significance of grain size
244 parameters. *J Sediment Petrol* 27:3–26

- 245 Gaillard M-J, Birks HH (2007) Paleolimnological applications. In: Elias SA (ed)
246 Encyclopedia of Quaternary Science, Volume 3, 2nd ed. Elsevier Science,
247 Amsterdam, pp 2337–2356
- 248 Kats NY, Kats SV, Kipiani MG (1965) Atlas and keys of fruits and seeds occurring in
249 the Quaternary deposits of the USSR . Nauka, Moscow (in Russian)
- 250 Körber-Grohne U (1964) Bestimmungsschlüssel für subfossile Juncus-Samen und
251 Gramineen-Früchte. In: Haarnagel W (ed) Probleme der Küstenforschung im
252 Südlichen Nordseegebiet 7. August Lax, Hildesheim, pp 1–47 (in German)
- 253 Körber-Grohne U (1991) Identification key fo subfossil Gramineae fruits. Probleme
254 der Küstenforschung im Südlichen Nordseegebiet 18:169–234
- 255 Kowalewski G (2014) Alogeniczne i autogeniczne składowe zarastania jezior:
256 hipoteza wahań poziomu wody. Polskie Towarzystwo Limnologiczne: Bogucki
257 Wydawnictwo Naukowe, Poznań (in Polish)
- 258 Książkiewicz M, Rączkowski W, Wójcik A (2016) Szczegółowa Mapa Geologiczna
259 Polski w skali 1:50000, Arkusz Osielec. Ministerstwo Środowiska, Warszawa (in
260 Polish)
- 261 Margielewski W (2001) Late Glacial and Holocene climatic changes registered in
262 forms and deposits of the Klaklowo landslide (Beskid Średni Range, Outer
263 Carpathians). Stud Geomorphol Carpatho-Balcanica 35:63–79
- 264 Matuszkiewicz W (2017) Przewodnik do oznaczania zbiorowisk roślinnych Polski.
265 Wyd. Naukowe PWN, Warszawa (in Polish)
- 266 Mauquoy D, van Geel B (2007) Mire and peat macros. In: Elias SA (ed) Encyclopedia
267 of Quaternary Science, Volume 3, 2nd ed. Elsevier Science, Amsterdam, pp
268 2315–2336
- 269 Mirek Z, Piękoś-Mirkowa H, Zając A, Zając M (2020) Vascular plants of Poland. An

270 annotated checklist. W. Szafer Institute of Botany, Polish Academy of Sciences,
271 Kraków

272 Moore PD, Webb JA, Collinson ME (1991) Pollen Analysis. Blackwell Scientific
273 Publications, Oxford

274 Passega R, Byramjee R (1969) Grain size image of clastic deposits. *Sedimentology*
275 13:233–252

276 Reille M (1992) Pollen et spores d'Europe et d'Afrique du Nord. Laboratoire de
277 Botanique Historique et Palynologie, Marseille (in French)

278 Szymczyk A (2015) Relacje między zespołami szczątków karpologicznych a
279 współczesną roślinnością małych, płytkich zbiorników wodnych. Wydawnictwo
280 Uniwersytetu Śląskiego, Katowice (in Polish)

281 Udden JA (1914) Mechanical composition of clastic sediments. *Bull Geol Soc Am*
282 26:655–744

283 van Geel B (1978) A palaeoecological study of Holocene peat bog section in
284 Germany and The Netherlands, based on the analysis of pollen, spores and
285 macro- and microscopic remains of fungi, algae, coprophytes and animals. *Rev*
286 *Palaeobot Palynol* 25:1–120

287 van Geel B, Bohnecke SJP, Dee H (1980) A palaeoecological study of an upper Late
288 Glacial and Holocene sequence from “De Borchert”, The Netherlands. *Rev*
289 *Palaeobot Palynology* 31:367–448

290 van Geel B, Buurman J, Brinkkemper O, Schelvis J, Aptroot A, van Reenen G,
291 Hakbijl T (2003) Environmental reconstruction of a Roman Period settlement site
292 in Uitgeest (The Netherlands), with special reference to coprophilous fungi. *J*
293 *Archaeol Sci* 30:873–883

294 van Geel B, Zazula GD, Schweger CE (2007) Spores of coprophilous fungi from

295 under the Dawson tephra (25,300 ¹⁴C years BP), Yukon Territory, northwestern
296 Canada. *Palaeogeogr Palaeoclimatol Palaeoecol* 252:481–485

297 Velichkevich F, Zastawniak E (2006) Atlas of the Pleistocene vascular plant
298 macrofossil of Central and Eastern Europe. Part 1: Pteridophytes and
299 Monocotyledons. W. Szafer Institute of Botany, Polish Academy of Sciences,
300 Kraków

301 Velichkevich F, Zastawniak E (2008) Atlas of the Pleistocene vascular plant
302 macrofossil of Central and Eastern Europe. Part 2: Herbaceous Dicotyledones.
303 W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków

304 Wentworth CK (1922) A scale of grade and class terms for clastic sediments. *J Geol*
305 30:377–392

306 Wójcik A, Rączkowski W (1994) *Objaśnienia do szczegółowej mapy geologicznej*
307 *Polski 1:50000, Arkusz Osielec*. Wydawnictwo Geologiczne, Warszawa, pp 1–63
308 (in Polish)

309 Zarzycki K (2002) Ecological indicator values of vascular plants of Poland. Polish
310 Academy of Sciences, W Szafer Institute of Botany, Kraków

311

312

14.7. Publikacja 3 – Tytuł

Pilch, J., Margielewski, W., Stachowicz-Rybka, R., Buczek, K., 2025. The Bølling-Older Dryas-Allerød transition (ca. 14,600–13,500 cal BP) in the palaeoecological record of the Kotoń landslide fen (the Outer Western Carpathians, S Poland) – from the local to extraregional perspective. *Radiocarbon* 1–21. <https://doi.org/10.1017/RDC.2025.10122>

MNISW (2024 rok): 140 pkt.

IF: (5-letni) 4,9; (2024 rok) 1,3

14.8. Publikacja 3 – Oświadczenia współautorów

Kraków, 20.10.2025

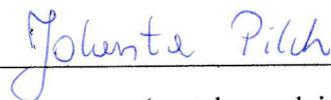
Mgr inż. Jolanta Pilch
Instytut Ochrony Przyrody
Polskiej Akademii Nauk
al. Adama Mickiewicza 33,
31-120 Kraków

OŚWIADCZENIE

Oświadczam, że w pracy:

Pilch, J., Margielewski, W., Stachowicz-Rybka, R., Buczek, K., 2025. The Bølling-Older Dryas-Allerød transition (ca. 14,600–13,500 cal BP) in the palaeoecological record of the Kotoń landslide fen (the Outer Western Carpathians, S Poland) – from the local to extraregional perspective. Radiocarbon 1–21. <https://doi.org/10.1017/RDC.2025.10122>

mój udział polegał na: wykonaniu prac w terenie, poborze próbek, analizie makroszczątków roślin, opracowaniu (statystycznym i graficznym) danych: makroszczątkowych, strat prażenia i datowań radiowęglowych (w tym przygotowywaniu modelu wiek-głębokość), przeprowadzeniu interpretacji paleośrodowiska oraz przygotowaniu manuskryptu (draft oraz recenzja i redagowanie). Mój udział w pracach wynosi 90%.



(czytelny podpis współautora)

Kraków, 20.10.2025

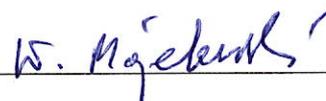
Dr hab. inż. Włodzimierz Margielewski, prof. IOP PAN
Instytut Ochrony Przyrody
Polskiej Akademii Nauk
al. Adama Mickiewicza 33,
31-120 Kraków

O Ś W I A D C Z E N I E

Oświadczam, że w pracy:

Pilch, J., **Margielewski, W.**, Stachowicz-Rybka, R., Buczek, K., 2025. The Bølling-Older Dryas-Allerød transition (ca. 14,600–13,500 cal BP) in the palaeoecological record of the Kotoń landslide fen (the Outer Western Carpathians, S Poland) – from the local to extraregional perspective. Radiocarbon 1–21. <https://doi.org/10.1017/RDC.2025.10122>

mój udział polegał na: pomocy w wykonaniu prac w terenie, konceptualizacji, nadzorze, pomocy w interpretacji paleośrodowiskowej i przygotowaniu manuskryptu (recenzja i redagowanie). Mój udział w pracach wynosi 4%.



(czytelny podpis współautora)

Kraków, 20.10.2025

Dr hab. Renata Stachowicz Rybka, prof. IB PAN
Instytut Botaniki im. W. Szafera
Polskiej Akademii Nauk
ul. Lubicz 46,
31-512 Kraków

OŚWIADCZENIE

Oświadczam, że w pracy:

Pilch, J., Margielewski, W., **Stachowicz-Rybka, R.**, Buczek, K., 2025. The Bølling-Older Dryas-Allerød transition (ca. 14,600–13,500 cal BP) in the palaeoecological record of the Kotoń landslide fen (the Outer Western Carpathians, S Poland) – from the local to extraregional perspective. Radiocarbon 1–21. <https://doi.org/10.1017/RDC.2025.10122>

mój udział polegał na: pomocy w przeprowadzeniu analizy makroszczątków roślin, konceptualizacji, nadzorze, pomocy w interpretacji paleośrodowiskowej i przygotowaniu manuskryptu (recenzja i redagowanie). Mój udział w pracach wynosi 4%.



(czytelny podpis współautora)

Kraków, 20.10.2025

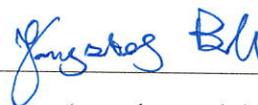
Dr Krzysztof Buczek
Instytut Ochrony Przyrody
Polskiej Akademii Nauk
al. Adama Mickiewicza 33,
31-120 Kraków

O Ś W I A D C Z E N I E

Oświadczam, że w pracy:

Pilch, J., Margielewski, W., Stachowicz-Rybka, R., **Buczek, K.**, 2025. The Bolling-Older Dryas-Allerød transition (ca. 14,600–13,500 cal BP) in the palaeoecological record of the Kotoń landslide fen (the Outer Western Carpathians, S Poland) – from the local to extraregional perspective. Radiocarbon 1–21. <https://doi.org/10.1017/RDC.2025.10122>

mój udział polegał na: pomocy w wykonaniu prac w terenie, konceptualizacji, pomocy w interpretacji paleośrodowiskowej, opracowaniu modelu wiek-głębokość oraz przygotowaniu manuskryptu (recenzja i redagowanie). Mój udział w pracach wynosi 2%.



(czytelny podpis współautora)

14.9. Publikacja 3

CONFERENCE PAPER

The Bølling-Older Dryas-Allerød transition (ca. 14,600–13,500 cal BP) in the palaeoecological record of the Kotoń landslide fen (the Outer Western Carpathians, S Poland)—from the local to extraregional perspective

Jolanta Pilch¹, Włodzimierz Margielewski¹, Renata Stachowicz-Rybka² and Krzysztof Buczek¹

¹Institute of Nature Conservation, Polish Academy of Sciences, al. Adama Mickiewicza 33, 31-120 Kraków, Poland and ²W. Szafer Institute of Botany, Polish Academy of Sciences, Lubicz 46, 31-512 Kraków, Poland

Corresponding author: Jolanta Pilch; E-mail: pilch@iop.krakow.pl

Received: 20 December 2024; **Revised:** 29 March 2025; **Accepted:** 25 April 2025

Keywords: Greenland ice cores correlation; landslide fen; late glacial; macrofossil analysis; multi-proxy

Abstract

In this paper a part of a new multi-proxy results obtained from the Kotoń landslide fen deposits (the Beskid Makowski Mountains, the Outer Western Carpathians, S Poland), including loss on ignition analysis, plant macrofossil analysis and radiocarbon dating is presented. The aim of the study was to verify whether the reconstructed local palaeoecological stages of the Kotoń fen development could be correlated with the Bølling-Older Dryas-Allerød sequence and to verify whether the rarely recognised short GI-1d/Older Dryas climate cooling affected the regional and local palaeoecological record of the Kotoń deposits. Results showed that four palaeoecological stages of development (poor-in-vegetation waterbody, waterbody with aquatic succession, calcareous extremely rich fen and moderately rich fen) determined for the Kotoń landslide fen deposits between ca. 14,600–13,500 cal BP stay in agreement with the earlier pollen division of the Kotoń deposits and with the extraregional chronology of the Greenland ice cores. The influence of GI-1d/Older Dryas climate cooling on the surrounding and regional vegetation was recognised for the deposits of Kotoń and other localities in a form of open-space habitats with herbs, shrubs and sparse tree stands, e.g. steppe-tundra, reflecting the cold and dry climatic conditions. In case of local vegetation and palaeohydrological changes, the Older Dyas climatic oscillation was recorded as a shallowing of the existing palaeo-waterbodies. Although for other localities this process was attributed to the dry climatic conditions, in case of Kotoń site more detail multi-proxy research is necessary to distinguish the climatic impact from the autogenic succession.

Introduction

In the region of the Beskid Makowski Mountains, the Outer Western Carpathians, S Poland, biogenic archives of the landslide fens, small mires formed within landslide depressions, contain exceptionally long late glacial minerogenic-organic sequences, reaching up to 2.5–3.5 m of thickness (Margielewski et al. 2022a). In the Kotoń landslide fen, lithological, pollen, plant tissue and carpological analyses and radiocarbon dating carried out during the previous studies revealed a distinct lacustrine-mire record of the Bølling-Older Dryas-Allerød transition (Margielewski 2001; Margielewski et al. 2003). Palynologically-determined local chronozones could not be, however, validated due to the lack of a detailed calibrated age scale. The importance of accurate age-depth model for the palynological profiles in the Carpathians is thoroughly recognized (Michczyński et al. 2013), also in respect to the possibility of conducting more extensive extraregional correlations (Margielewski et al. 2022b).

Traditionally, for the late glacial period Bølling and Allerød climate warmings are separated by a short (ca. 100–200 years) climate cooling of the Older Dryas, a succession based on biostratigraphic record of the Scandinavia region (Iversen 1954). Later these phases were also adopted as formal chronozones for this part of Europe, assigning to the Bølling Chronozone (including the Oldest Dryas interval) time boundaries from 13.0 to 12.0 k uncal BP, to the Older Dryas Chronozone from 12.0 to 11.8 k uncal BP and to the Allerød Chronozone from 11.8 to 11.0 k uncal BP (Mangerud et al. 1974). The classical stratigraphic subdivision of the late glacial across different regions of Europe seems to be, however, strongly diverse and problematic (De Klerk 2004; Van Raden et al. 2013). For example, the Older Dryas climatic deterioration is very weak or absent in the palaeo-records from the British Isles, therefore Bølling and Allerød are considered there as a single interstadial whereas separation of the Older Dryas is questioned (Watts 1980). Similar problem with the Older Dryas distinction was recognized for the Alps, where it could often only be registered at higher altitudes closer to ecotone (Lotter et al. 1992; Welten 1982).

For the North Atlantic region, GRIP Greenland ice core (event stratigraphy based on the oxygen isotope record) was suggested as a stratotype for the 22.0 to 11.5 k GRIP yr BP (ca. 19.0–10.0 k BP), with recommendation for replacing the classical terminology: “Bølling,” “Older Dryas,” “Allerød,” and “Younger Dryas” with a new scheme (Björck et al. 1998). In this scheme, the Bølling-Allerød interval seemed to correspond to the Greenland Interstadial 1 (GI-1), dated to 12.65–14.7 k GRIP yr BP, subdivided into three warmer episodes, GI-1a, 1c and 1e, separated by the colder ones, GI-1b and 1d. On the other hand, it was stressed that Greenland ice core chronology should not replace the regional terrestrial stratigraphic divisions but to be used as extraregional reference for them (Litt et al. 2001; Lowe et al. 2008; Van Raden et al. 2013). Although the risk of potential miscorrelation with some other short-lasting late glacial climatic events of the high-resolution oxygen-isotope records from the Greenland ice cores is clearly emphasized (Rasmussen et al. 2014), commonly the Bølling climatic oscillation is correlated with GI-1e episode, Older Dryas with GI-1d, and early Allerød with GI-1c (Van Raden et al. 2013). The requirement for such correlation between terrestrial records and Greenland ice core stratigraphy is an independent absolute chronology derived from radiocarbon dates (Lowe et al. 2008), as well as from other dating method e.g. varve chronology (Litt et al. 2001). There is a growing number of the late glacial studies investigating sequences which contain the Bølling-Older Dryas-Allerød transition and attempting to correlate these sequences with the Greenland event stratigraphy (Ammann et al. 2013; Bos et al. 2013, 2017; Dzieduszyńska and Forsytek 2019; Feurdean and Bennike 2004; Kołaczek et al. 2015; Litt et al. 2001; Moska et al. 2022).

Palaeo-records with the Older Dryas climatic oscillation distinguished as a traditional biostratigraphic zone or chronozone (Iversen 1954; Mangerud et al. 1974) based on pollen data are more numerous than those in which Older Dryas is correlated with GI-1d episode of the Greenland event stratigraphy based on absolute chronology. Frequently, in the flat areas of Europe, a former foreland of retreating ice-sheet, some distinct Older Dryas deposits were recorded at localities connected with late glacial aeolian activity, e.g. dunes, sand covers, loess areas (Wasylikowa 1964). It was suggested that vegetation growing on these types of unstable ground may be more prone to climate deterioration (Burdukiewicz et al. 2007; Latałowa and Nalepka 1987) e.g. intense winds and give more pronounced response in palynological profiles.

Older Dryas deposits have been also documented in the lacustrine late glacial-Holocene sequences of the Polish Lowlands. In the Lake Gościąg, Older Dryas was marked (however not very distinctively) as a short-lasting cooling phase during which the opening of forest habitats occurred, probably intensifying a shore slumping process and sand deposition (Goslar et al. 1998; Ralska-Jasiewiczowa et al. 1998). Older Dryas climatic oscillation was readily pronounced in palynological profiles of Osłonki palaeo-lake, both as a drop in abundance of tree pollen, an increase in abundance of shrubs and herbaceous plants, as well as a rising number of plant taxa representing wet and aquatic habitats (Nalepka 2005).

Further toward the East European Plain, the Older Dryas deposits were identified in the bottom of the lacustrine sequences of a few Belarusian lakes (Novik et al. 2010; Zernitskaya 1997). In the eastern parts of Poland, in the area of today Puszcza Knyszyńska during the Older Dryas climatic phase high water

table conditions prevailed, facilitating the onset of *Taboły mire* organic succession (Drzymulska 2010). For the Wolbrom peatland site located in the Silesian-Cracovian Upland, the influence of Older Dryas climate cooling was recognized, however, the interpretation of the resulting vegetation changes was ambiguous (Latałowa and Nalepka 1987). In the adjacent region of the Sandomierz Basin, sites with peatland and alluvial deposits revealed only a few mm thick horizon of the Older Dryas phase, characterized by tundra vegetation with sparse tree stands (Nalepka 1994).

Older Dryas was found in intermontane depressions of the Outer Western Carpathians. In Tarnowiec site (Jasło-Sanok Depression, SE Poland) it comprised several cm of sand-organic sediments, with low concentration of pollen in a bottom part and pollen diagrams suggesting the predominance of a park-woodland landscape and abundance of shrubs and herbs at that time (Harmata 1987). In the Nowy Targ Basin (S Poland), Older Dryas deposits were found within the profile of the raised bog Na Grełu (Koperowa 1961). Here, it is represented by ca. 35 cm of mineral deposits with pollen assemblage interpreted as the treeless shrub tundra conditions.

Palaeoenvironmental studies of the landslide fen deposits of Klakłowo and Kotoń sites, located in the mid-altitudes of the Beskid Makowski Mountains (the Outer Western Carpathians) revealed the exceptionally thick, ca. 0.5 m, sequence of mineral deposits attributed to the Older Drays climatic phase (Margielewski 2001; Margielewski et al. 2003, 2022b). In the High Tatras (the Outer Carpathians, S Poland) sedimentological studies from Czarny Staw Gąsienicowy lakes revealed that the pre-Allerød mineral deposits characterized by a massive type of bedding may be attributed to the cooling phases of the Oldest Dryas and the Older Dryas stadials (Baumgart-Kotarba and Kotarba 1993). The pre-Allerød section of the palynological diagrams exhibits an increase in non-arboreal pollen values connected with open, steppe-tundra conditions and probable occurrence of timberline below the altitude of the Czarny Staw Gąsienicowy lake at that time. With some uncertainty this section was interpreted as the Older Dryas Stadial (Obidowicz 1993, 1996). More ambiguous are pre-Allerød deposits from Żabie Oko (Baumgart-Kotarba et al. 1994), although pollen data also suggest the Older Dryas cooling as a probable time of their accumulation (Obidowicz 1993, 1996).

In this paper a part of a new multi-proxy results obtained from the Kotoń landslide fen deposits (the Beskid Makowski Mountains, the Outer Western Carpathians, S Poland), including loss on ignition analysis (LOI), plant macrofossil analysis and radiocarbon dating is presented. The aim of the study is:

1. to verify whether there is an agreement between reconstructed local palaeoecological stages of the Kotoń fen development (500–300 cm depth interval of the Kotoń sediment sequence) and the Bølling, Older Dryas and the Allerød climatic oscillations defined according to the previous pollen division of the Kotoń fen deposits (Margielewski et al. 2003) and extraregional absolute chronology of the Greenland ice cores (Rasmussen et al. 2014).
2. to verify whether the short GI-1d/Older Dryas climate cooling occurring 13,904–14,025 yr BP (Rasmussen et al. 2014), being rarely recognised in late glacial sequences across Europe, affected also the regional and local palaeoecological record of the Kotoń landslide fen deposits. If confirmed, Kotoń locality would be considered as a unique and rare occurrence of the Older Dryas deposits not only in a scale of the Carpathians and Poland but also in the scale of Europe, contributing to the better understanding of the short climatic oscillations occurring throughout the late glacial period.

Materials and methods

Site description

Geological and geomorphological setting

The study site is located in the south of Poland, in the Outer Western Carpathians, a mountain group built of the Late Jurassic-Early Miocene flysch rocks (Książkiewicz 1972) (Figure 1A and 1B). The Kotoń landslide and the peatland filling the landslide's sub-scarp depression, are situated in the southern

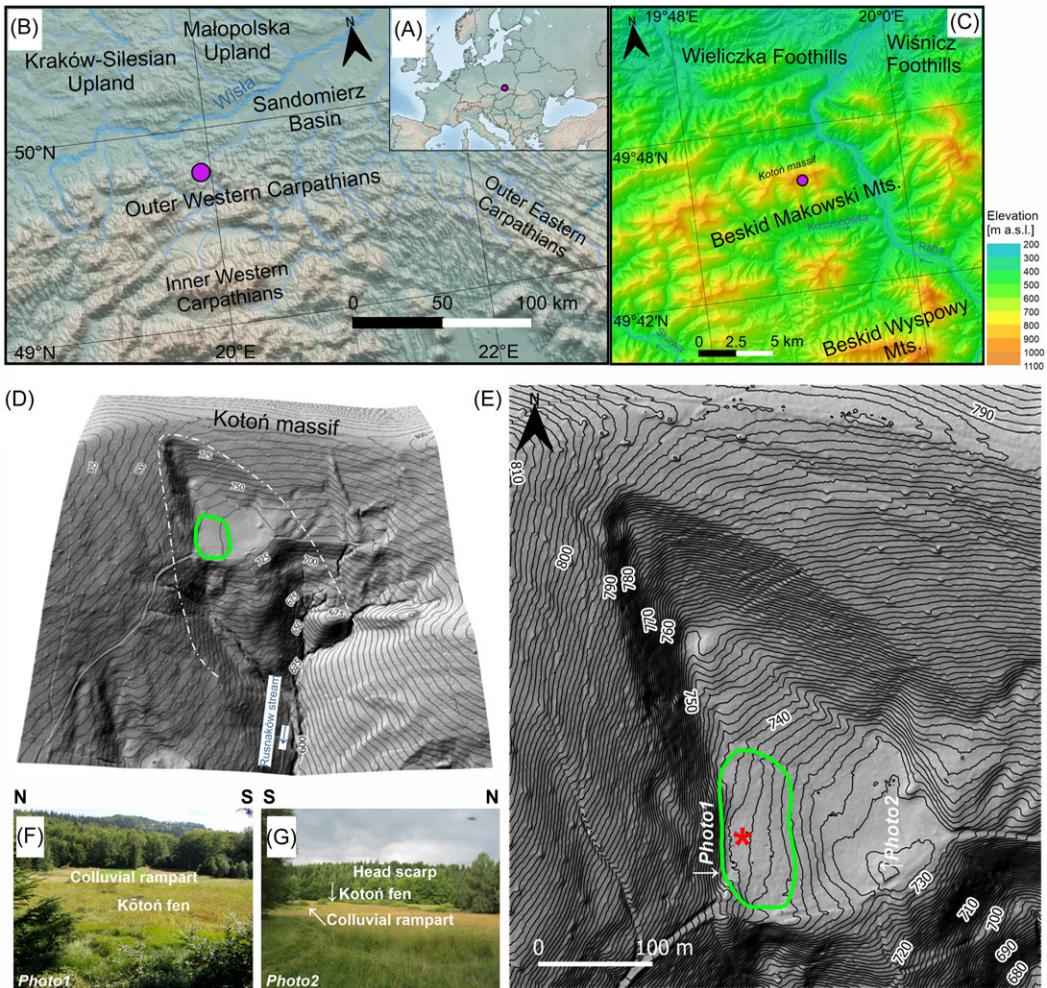


Figure 1. Location of the Kotoń landslide fen (purple circle) in Europe (A), the region of the Outer Western Carpathian (B) and the Beskid Makowski Mountains (C); (D) Kotoń landslide zone (outlined with the dotted line) with the position of the Kotoń landslide fen (green solid line), (E) present-day area (green solid line) of the fen with a drilling site (red star); (F) and (G) present-day vicinity of the Kotoń fen (photo by Włodzimierz Margielewski). Sources of basemaps: part (A) <https://www.natureearthdata.com/downloads/10m-cross-blend-hypso/cross-blended-hypso-with-relief-water-drains-and-ocean-bottom/>; part (B) digital terrain model DTM <https://download.gebco.net/> draped with the basemap of the part (A); part (C) DTM from WCS service <https://mapy.geoportal.gov.pl/wss/service/PZGIK/NMT/GRID1/WCS/DigitalTerrainModelFormatTIFF.>

slope of the Kotoń massif, belonging to the Beskid Makowski Mountains (Figure 1C). The entire landslide zone developed within the thick-bedded Magura sandstones of the Siary Subunit, Magura Unit (Książkiewicz et al. 2016; Wójcik and Rączkowski 1994). The landslide lies close to the massif crest (the pass between the Mt. Kotoń, 857 m a.s.l., and the Mt. Pękalówka, 835 m a.s.l.) and formed as a result of the development of the upper part of the Rusnaków stream (left tributary of the Krzczonówka stream) (Figure 1C and 1D) (Margielewski 2001; Margielewski et al. 2003). Landslide form has a shape of a broad wedge with two linear main scarps (ca. 15–30 m high) and a flat area of the landslide colluvium in between them (Figure 1D and 1E). A longitudinal depression formed at the foot of the western scarp of the Kotoń landslide (Figure 1D and 1E), limited from the east by elongated colluvial

rampart (Figure 1F and 1G). The depression is about 50 m wide, 100 m long and up to 5 m deep, filled up with organic-minerogenic sediments of the Kotoń landslide fen.

Climate, hydrology and vegetation

Climate of the Beskid Makowski Mountains is moderately warm (mean air temperature: 8.0–8.5°C) with significant amount of precipitation (mean annual sum: 800–1000 mm), influenced by mountainous land relief (Tomczyk and Bednorz 2022). Prevailing winds blow from the west to the east and the Kotoń site is located on the leeward slope. Similarly to the adjacent regions, temperature inversions occur in the river valleys. Beside the Rusnaków stream originating in the lower part of the Kotoń landslide, there are no permanent streams flowing down from the head scarp and slopes, although the temporary ones are likely (Figure 1E). Two altitudinal-climatic vegetation belts occur in this region: submontane (< 550 m a.s.l.), with the indicator forest community being the colline form of the *Tilio-Carpinetum* association, and nowadays covered by secondary grass-rich communities, the so-called oak-hornbeam meadows (*Arrhenatherion* alliance), and the lower montane vegetation belt (550–870 m a.s.l.), represented by the fertile Carpathian beech forest *Dentario glandulosae-Fagetum* and by the montane acidophilous beech forest, *Luzulo luzuloides-Fagetum* with secondary communities of seminatural meadows and pastures (*Polygono-Trisetion* alliance) (Mirek 2013). Mean annual growing season lasts 220–230 days (Tomczyk and Bednorz 2022).

Coring and sampling

Sediment core was probed with the INSTORF Russian peat sampler (diameter: 8 cm) from the axial part of the Kotoń sub-scarp depression (49°46'5.12"N; 19°54'12.96"E, 739 m a.s.l., Fig. 1E). Drilling spot was close (0.5 m) to the site which was examined during earlier study (Margielewski 2001; Margielewski et al. 2003), however, this time the maximum reached length of the core was greater: 500 cm comparing to the previous 450 cm. Furtherly, the core was sliced into samples in the following scheme: 2.5 cm for the 500–300 cm depth interval and 5 cm for the 300–0 cm depth interval. Samples were subjected to the loss on ignition and plant macrofossil analyses and radiocarbon dating (other multi-proxy analyses will be presented in a separate paper). For the purpose of this study, the depth section of 500–300 cm comprising the Bølling-Older Dryas-Allerød transition was selected.

Radiocarbon dating and age-depth model

Material for Acceleration Mass Spectrometry (AMS) dating was collected during the plant macrofossil analysis from a depth section of 440–77 cm of the sediment core at sampling depths representative for changes in lithology. Below 440 cm botanical remains were insufficient for AMS dating, whereas the depth section above 77 cm (Holocene sediment) was not a target of the current study. For the depth range 440–77 cm well-preserved plant material was identified to species level and multiple macrofossil types were selected for dating, including plant fruits, seeds, leaves and needles.

In total, six radiocarbon dates were obtained: five samples were submitted to the Laboratory of Absolute Dating in Kraków, Poland, in collaboration with the Center For Applied Isotope Studies, University of Georgia, U.S.A, whereas one sample of the smallest weight was submitted to Beta Analytic, Inc. Miami, Florida, U.S.A (sample 435–431 cm, Beta-692394). To standardize the calibrated results, the obtained ¹⁴C dates BP were further calibrated using the OxCal v. 4.4.4 software (Bronk Ramsey 2009, 2021) and the IntCal20 calibration curve (Reimer et al. 2020).

Based on six ¹⁴C AMS dates the Bayesian age-depth model was constructed for the Kotoń sediment sequence. The modelling of age-depth curve was conducted in the OxCal v. 4.4.4 software (Bronk Ramsey 2009, 2021) using the P_{sequence} function, interpolation = 2 (0.5 cm), parameters k0 = 1 and log10(k/k0) = U(−1,1), with the IntCal20 calibration curve. At a depth of 120 cm a *Boundary command*

was introduced to reflect a significant change in lithology (there is a sudden reduction in values on the loss on ignition curve associated with admixture of silt to sedge-moss fen peat accumulation) and plant macrofossil assemblages (macrofossil data from 300–0 cm are not presented in this paper). A mean (μ) value of the modelled age (values rounded to tens) expressed in cal BP and sedimentation rate expressed in mm year⁻¹, were obtained.

Loss on ignition and peat type

During the loss on ignition analysis (LOI) sediment slices (2.5 cm thick) underwent the ignition process in a muffle furnace at 550°C according to the standard procedure of Heiri et al. (2001). After burning, samples were weighed again in order to determine the loss in organic matter content and the loss on ignition curve (weight loss expressed in %) was plotted. Peat type description was based on the earlier study (Margielewski 2001; Margielewski et al. 2003), in which it was carried out by plant tissue analysis and classification of Tolpa et al. (1967).

Macrofossil analysis and zonation

Disintegrated material was mildly washed with running water through mesh sieve of 200 μ m diameter. Macrofossils identification was performed with ZEISS Stemi 508 stereomicroscope at 10–16 \times magnifications. Macrofossils of plants (fruits, seeds, needles, oospores etc.) and animals (ephippia, statoblasts, gemmules etc.) were recognized according to appropriate atlases, keys and publications (Aalto 1970; Anderberg 1994; Berggren 1969, 1981; Birks 2013; Cappiers et al. 2012; Kats et al. 1965; Körber-Grohne 1964, 1991; Kowalewski 2014; Mauquoy and van Geel 2007; Velichkevich and Zastawniak 2006, 2008). Collection of modern diaspores and specimens of fossil flora from the National Biodiversity Collection of Recent and Fossil Organisms stored at W. Szafer Institute of Botany PAS in Kraków (herbarium KRAM) was also used for this purpose. Botanical nomenclature for vascular plants was based on Mirek et al. (2020) and for mosses (Bryopsida) on Lüth (2019), phytosociological nomenclature was adopted after Pladias – Database of the Czech Flora and Vegetation, whereas ecological requirements of plants were based mostly on Zarzycki (2002) and other references. Plant taxa representing trees, shrubs and dwarf shrubs were gathered into one group, whereas other vascular plants, Bryopsida and Characeae were grouped according to habitat moisture level (dry, fresh and moist, mire and aquatic), also in order to better present the terrestrial and aquatic vegetation successions. Taxa of animal and other remains were put into group named Others. All data were plotted on the macrofossil diagram using Tilia software (Grimm 1991) as absolute macrofossil counts per sample volume (8.0–24.0 cm³, mean: 15.80 cm³). In case of Bryopsida, relative abundances of identified species were expressed as percentage of the total amount of well-preserved moss stems and presented as Bryopsida composition in the sub-section of the macrofossil diagram.

Zonation of the Kotoń sediment sequence was carried out for macrofossil data (absolute counts standardized to the same volume 16 cm³, excluding Bryopsida species expressed in percentages), using constrained incremental sum of squares cluster analysis (CONISS, Grimm 1987). The broken stick model (Bennett 1996) was used to establish the number of statistically significant zones. Cluster analysis was conducted in R version 4.2.2 (R Core Team 2022) and using package Rioja (Juggins 2022). The final depth ranges of the palaeoecological stages of development were determined based on cluster analysis results and visual inspection of the macrofossil diagram.

Results and discussion

Absolute chronology and sedimentation rate

The obtained uncalibrated and calibrated AMS radiocarbon dates are presented in Table 1. The agreement index A_{model} of the Kotoń age-depth model equals 91% and it is greater than the recommended

Table 1. Results of radiocarbon dating of the Kotoń landslide fen deposits. * – MKL: Laboratory of Absolute Dating in Kraków, Poland, in collaboration with the Center For Applied Isotope Studies, University of Georgia, U.S.A.; Beta: Beta Analytic, Inc. Miami, Florida, U.S.A. Calibration conducted in OxCal v4.4.4 Bronk Ramsey (2021) with IntCal20 calibration curve (Reimer et al. 2020). Selection and identification of plant macrofossils for AMS dating was done by Jolanta Pilch and Renata Stachowicz-Rybka

No.	Depth (cm)	Material (macrofossil type)	Lab code*	Age ¹⁴ C (uncal BP)	Calibrated age 2σ 95.4% (cal BP)	Mean μ (cal BP)	Sigma σ (cal years)	Context of dating
1	77.5–80	<i>Sambucus racemosa</i> fruits, <i>Rubus idaeus</i> fruits	MKL-A6645	6805 ± 28	7682–7587 (95.4%)	7639	26	Minerogenic cover
2	180–182.5	<i>Carex rostrata</i> fruits	MKL-A6591	10,159 ± 31	11,935–11,698 (92.9%), 11,665–11,650 (2.5%)	11,804	72	Sedge-moss fen peat
3	262.5–265	<i>Pinus sylvestris</i> needles, leaves fragments (not identified)	MKL-A6590	11,242 ± 34	13,226–13,218 (1.4%), 13,180– 13,093 (94.0%)	13,140	28	Moss fen peat
4	325–327.5	<i>Carex rostrata</i> fruits	MKL-A6589	11,967 ± 33	14,021–13,914 (45.8%), 13,884–13,766 (49.6%)	13,890	80	Moss fen peat/Alder peat
5	390–392.5	<i>Alchemilla</i> sp. fruits, <i>Carex rostrata</i> fruits, <i>Valeriana simplicifolia</i> / <i>dioica</i> fruits, Poaceae fruit	MKL-A6588	11,981 ± 33	14,023–13,906 (48.3%), 13,892–13,785 (47.1%)	13,899	75	Organic-minerogenic sediment
6	431–435	<i>Alchemilla</i> sp. fruits, <i>Carex rostrata</i> fruits, <i>Carex</i> sp. trigonus fruits	Beta-692394	12,300 ± 40	14,440–14,083 (83.5%), 14,805–14,710 (12.0%)	14,302	195	Horizon with numerous macrofossils within silt sequence

Loss on ignition and peat type

The results of the loss on ignition analysis and peat type descriptions are given in Figure 2 and Supplementary Material-Table 1. In general, the investigated section of the Kotoń profile consists of minerogenic material (silt with different admixtures) showing low LOI values (ca. <10%) in a depth interval of 500–405 cm and organic deposits (mostly moss fen peat) with LOI values growing up to ca. 85% in the 405–300 cm depth interval. The detail interpretation of the LOI and peat type results along with other proxies is given in Table 2 and Figure 4.

Macrofossil data and palaeoecological stages of the Kotoń landslide fen development

Four palaeoecological stages KT-1 to KT-4 (with two substages for stage 1 and 4) for the depth interval 500–300 cm of the Kotoń sediment sequence were eventually determined. Detail description of macrofossil assemblages of these zones is given in Supplementary Material-Table 1, whereas macrofossil diagram is presented in Figure 3. The detail palaeoecological interpretation of the stages is given in Table 2 and Figure 4.

Older dryas (GI-1d) in the Kotoń and other palaeo-records possessing absolute chronologies

In general, the Older Dryas climatic oscillation was related to the reappearance of cold and dry continental climate. In the Kotoń sediment sequence, during the stage KT-2 the inferred climatic conditions around the Kotoń waterbody seem to be arctic/alpine (Figure 3, Table 2). Within the Kotoń waterbody itself, development of the aquatic organisms' successions with Bryopsida dominated by *Sarmentypnum trichophyllum* is indicative for the occurrence of littoral zone presumably resulting from the shallowing of the lake existing during the stage KT-1 (GI-1e/Bølling). On the other hand, if no deeper lake existed during the stage KT-1, the aquatic conditions of the stage KT-2 could be explained by low temperatures and related low evapotranspiration occurring under cold and dry conditions (low precipitation), which allowed a shallow waterbody to persist.

Stage KT-2 lasted from ca. 14,070 ± 72 to ca. 13,900 ± 56 cal BP (ca. 170 years), what also correspond well to a short GI-1d/Older Dryas climate cooling occurring 14,025–13,904 yr BP according to the Greenland ice cores event stratigraphy (Rasmussen et al. 2014). Plant formations of the Kotoń fen surrounding inferred for each of the palaeoecological stages (with some exception for KT-1 which probably records the local conditions of the landslide) stay in agreement with the earlier pollen-based chronozones (Margielewski et al. 2003) (Figure 4): Bølling characterized by park tundra with *Betula* and *Pinus* corresponds to KT-1a and 1b, Older Dryas represented by grass-shrub tundra is related to KT-2 and KT-3, and Allerod-1 characterized by the immigration of *Pinus* and *Betula* forest corresponds to KT-4a and 4b. A slight discrepancy in the depth extent between pollen-based Older Dryas chronozone and macrofossil-based stage KT-2 (GI-1d/Older Dryas climate cooling according to NGRIP event stratigraphy) could be explained by the fact, that these two datasets were obtained from two different sediment cores, located however close to each other (0.5 m between drilling spots). Moreover, the specificity of macrofossil and pollen method must be taken into consideration, as they reflect the local and regional vegetation changes, respectively (Birks 2013). In case of differences in time range between previously determined pollen-based chronozones for Kotoń (Margielewski et al. 2003) and Greenland ices cores event stratigraphy (Rasmussen et al. 2014), it is important to stress that GI-1d / Older Drays climate cooling is clearly defined in term of time range (14,025–13,904 yr BP), whereas for many palaeo-records (including Kotoń site) the Older Drays climate cooling was recognized as based solely on pollen diagrams, without a reference to specific time boundaries defined within extraregional chronologies (Björck et al. 1998; Mangerud et al. 1974; Rasmussen et al. 2014). Therefore, the discrepancies in the depth extent between pollen-based and chronology-based divisions of the sediment sequence are possible (Margielewski et al. 2022a).

Table 2. Palaeoecological stages of the Kotoń landslide fen development

Depth and age range of the stage	Description (see also Figures 2–4)
Stage KT-1a (500–431 cm, > ca. 14,240, ± 103 cal BP) corresponding to GI-1e/Bølling and possibly also to GS-2/ Oldest Dryas	Sedimentation of minerogenic material (silt with sand and debris admixtures) and a few aquatic organisms (Characeae, Ostracoda, <i>Daphnia</i> sp., <i>Simocephalus</i> sp., Chironomidae) at different depths of the 500–431 cm interval, indicate that during the stage KT-1a a waterbody developed in the Kotoń subscarp depression (Figure 3). A general scarcity of macroremains could suggest unfavorable living conditions in the waterbody, absence of surrounding vegetation or a lack of plant remains transport to the waterbody due to limited precipitation. The proximity of the eulittoral zone is signaled by macrofossils of <i>Carex rostrata</i> , <i>Scirpus sylvaticus</i> and <i>Juncus</i> sp. An episode of waterbody shallowing and vegetation encroachment is recorded in the upper part of this zone (at a depth of 435–431 cm) with plants of minerotrophic fens and fen meadows represented by <i>Carex rostrata</i> and <i>Valeriana simplicifolia/dioica</i> . The most abundant fruits of this layer belong to <i>Alchemilla</i> sp. which implies mesic to wet stands within the different types of grasslands. Debris material found in the zone KT-1b indicates that dynamic slope processes occurred around the Kotoń sub-scarp depression probably enhanced by the lack of vegetation cover. As these phenomena could results from the local conditions of the freshly formed landslide colluvium, their interpretation in term of regional climatic changes should be done with caution (e.g. lack of vegetation due to severe climatic conditions) (Margielewski 2018).
Stage KT-1b (431–405 cm, from ca. 14,240 ± 103 to ca. 14,070 ± 72 cal BP, ca. 170 years) corresponding to GI-1e/ Bølling	Stage KT-1b is characterized by continuing aquatic conditions (Characeae, <i>Batrachium</i> sp., Ostracoda, <i>Daphnia</i> sp.), however, there is a noticeable change in the character of accumulated minerogenic material from silt with sand and debris admixtures to more clayey homogenous silt (Figures 2 and 3). <i>Carex magellanica</i> is the most abundant and common among the mire plants, possessing more preference toward cold conditions than other sedges present in the zone KT-1: <i>Carex rostrata</i> and <i>Carex diandra</i> . Nowadays, <i>Carex magellanica</i> subsp. <i>irrigua</i> has optimum in boreal zone, it is found at high altitudes (subalpine and alpine) of Alps as well as more rarely it is present in other localities of Central Europe, e.g. Orava region in Slovakia (Dítě and Pukajová 2003 and reference therein). In the latter site, it occupies less waterlogged hummocks occurring in acidic habitat of floating fen. It is also classified among glacial relict species of the Western Carpathians as the highest-ranked species diagnostic for the acidic peatlands (Dítě et al. 2018). Continued occurrence of <i>Alchemilla</i> sp., confirm open-space conditions, whereas fruit of <i>Solidago virgaurea</i> could be transported from some drier stand.
Stage KT-2 (405–367.5 cm, from ca. 14,070 ± 72 to ca. 13,900 ± 56 cal BP, ca. 170 years)	In the KT-2 zone, judging by the continuous occurrences and the highest abundance of aquatic organisms in the entire 500–300 cm section (Characeae, <i>Batrachium</i> sp., <i>Potamogeton alpinus</i> , Ostracoda, <i>Daphnia</i> sp., <i>Simocephalus</i> sp., <i>Ceriodaphnia</i> sp., Porifera, <i>Plumatella</i> , Oribatid mites, Chironomidae), vegetation

(Continued)

Table 2. (Continued)

Depth and age range of the stage	Description (see also Figures 2–4)
corresponding to the GI-1d/Older Dryas	<p>succession has progressed in the Koton waterbody and a change to more gyttja-like sedimentation with increasing amount of organic matter occurred (Figure 2 and 3). Macrophytes represented by Characeae, <i>Batrachium</i> sp. and <i>Potamogeton alpinus</i> are often found in the late-glacial limnic records as pioneering species colonizing lakes (Gałka and Sznal 2013; Kofaczek et al. 2015; Lewandowska et al. 2023). Studies showed that concentration of Characeae oospores amounting for more than 100 oospores per 100 cm³ is characteristic for the <i>in situ</i> occurrence of Characeae plant community class <i>Charetea</i> Fukarek ex Krausch 1964, commonly described as Characeae meadows (Szymczyk 2015 and reference therein). In the Kotoń palaeo-waterbody deposits concentration of Characeae oospores is many times greater than the abovementioned value what implies that the submerged Characeae meadows could spread at the bottom of the Kotoń waterbody at that time. Characeae presence suggests that the water conditions were well-transparent, oligo- to mesotrophic and mildly acidic-alkaline (Pelechaty et al. 2007). Endocarps of <i>Potamogeton alpinus</i> are characteristic for the onset and ending of interglacials and interstadials, whereas at present day it is more a glacial relict with distribution restricted mostly to boreal and mountain zones (Velichkevich and Zastawniak 2006). <i>Potamogeton alpinus</i> confirms clear-water and rather nutrient-poor conditions, indicating also slightly acidic to moderately alkaline environment and a distinct fine-grained substrate rich in organic matter (Borsukevych 2013; Hrivnák et al. 2011). Aquatic conditions are also confirmed by the composition of Bryopsida group dominated by <i>Sarmentypnum trichophyllum</i> (more than 90% of all Bryopsida) which could grow in the shallower part of the water pool. Moreover, <i>Hygrohypnum ochraceum</i> and <i>H. molle</i> s. lat. are species indicative of a flowing water and stony substrate, therefore the occurrence of the stony stream inflow to the waterbody should be taken into consideration. Also species related to mire in waterbody littoral were present in small abundances, either regularly throughout the zone (<i>Philonotis calcarea</i>, <i>Sarmentypnum exannulatum</i>, <i>Aulacomnium palustre</i>) or as sporadic occurrences (<i>Scurio-hypnum reflexum</i>, <i>Kindbergia</i> cf. <i>praelonga</i>, <i>Rhizomnium punctatum</i>, <i>Plagmonium</i> cf. <i>ellipticum</i> and <i>Palustriella decipiens</i>).</p> <p>During the KT-2 stage, the Characeae-dominated Kotoń waterbody was fringed with mire habitats represented mostly by Bryopsida and sedges (<i>Carex</i>) (Figure 3). Vascular plants were dominated by small sedges <i>Carex nigra</i> and sporadically by <i>Carex diandra</i> and tall sedges <i>Carex rostrata</i> and <i>Carex magellanica</i> and could form a plant community resembling the alliance <i>Caricion canescenti-nigrae</i> Nordhagen 1937. This plant community is characteristic for emmersive vegetation of moderately rich fen (Hájek et al. 2006) with developed moss layer, constantly waterlogged, where it can</p>

(Continued)

Table 2. (Continued)

Depth and age range of the stage	Description (see also Figures 2–4)
	<p>form initial mats fringing waterbodies. The mosaic habitats around the Kotoń waterbody were differentiated according to water level conditions and characterized by the development of some productive tall-herb stands. In the prolonged water-logged conditions <i>Epilobium palustre</i> and <i>Valeriana simplicifolia/dioica</i> could thrive, whereas at more elevated wet meadow-like patches characterized by fluctuating water level, <i>Ranunculus repens</i>, <i>Alchemilla</i> sp. and <i>Melandrium rubrum</i> used to grow, indicating also that trophy and access to light varied locally. Nutrient-demanding <i>Urtica dioica</i> and <i>Heracleum sphondylium</i> may represent fresh/ moist conditions.</p> <p>In the further distance from the Kotoń waterbody, or at the slopes rising around the basin, open, dry/fresh and base-rich habitats occurred, as indicated by a distinct presence of heliophilous taxa <i>Dryas octopetala</i>, <i>Androsace</i> cf. <i>chamaejasme</i> and Caryophyllaceae. <i>Dryas octopetala</i> is an arctic-alpine dwarf-shrub, presently growing in the arctic tundra and rocky meadows of the Carpathians, Alps and other mountainous areas (Elkington 1971). It is common in fossil records during the glaciation periods (Velichkevich and Zastawniak 2008), confirming the cold climatic conditions for the zone KT-2. <i>Androsace</i> cf. <i>chamaejasme</i> is also an arctic-alpine species, nowadays occurring in calcareous grasslands of the alpine belt of the Carpathians (Mirek 2013), together with a slightly more moisture-preferring <i>Potentilla</i> cf. <i>crantzii</i>. Therefore, during the stage KT-2 the environment around Kotoń basin could resemble arctic steppe-tundra and/or alpine rocky meadows. Moreover, some tree stands or single tree individuals could grow in this open landscape during the zone KT-2, as macrofossils of Coniferae and <i>Betula</i> species start to occur sporadically.</p>
<p>Stage KT-3 (367.5–345 cm, from ca. 13,900 ± 56 to ca. 13,820 ± 68 cal BP, ca. 80 years) corresponding to the transition from the GI-1d/Older Dryas to GI-1c/Allerød</p>	<p>The oligo-mesotrophic lake, which developed during the stage KT-2, seems to be shallowing/overgrowing and transforming into (calcareous) extremely rich fen (Hájek et al. 2006) during the stage KT-3. This process can be connected to the natural autogenic succession. A change into fen is reflected in an almost total disappearance of Characeae oospores, <i>Batrachium</i> sp. and <i>Potamogeton alpinus</i> and significantly lowered abundance of <i>Daphnia</i> sp., Porifera and other animal remains. Bryopsida composition also shows a prominent change: it becomes dominated by calciphilous <i>Calliergon giganteum</i> (up to 90% of the total Bryopsida abundance) which at some depths decline at the expense of the other calciphilous species: <i>Philonotis calcarea</i> and <i>Palustriella decipiens</i>. Calcareous character of the fen is also suggested by the minor presence of <i>Ptychostomum pseudotriquetrum</i> and <i>Drepanocladus trifarius</i>. A process of top-to-bottom overgrowing with floating mats cannot be excluded as the terrestrialization mechanism of the Kotoń palaeo-lake. During the stage KT-3 peat-forming plants became more wide-spread and thrived in continuous water-logged conditions (Figure 3). Therefore,</p>

(Continued)

Table 2. (Continued)

Depth and age range of the stage	Description (see also Figures 2–4)
Stage KT-4a and b (345–300 cm, from ca. 13,820 ± 68 to ca. 13,500 ± 115, ca. 320 years) corresponding to the GI-1c/Allerød	<p>moss fen peat accumulation could take place what is also expressed in a rise of the LOI curve values (Figure 2). Macrofossils of sedges become noticeably more abundant (especially <i>Carex nigra</i>), except for <i>Carex magellanica</i>, which declines (possibly due to the warming climatic conditions) supporting an increase in productivity and stronger competition of other sedges. Vegetational composition and moisture-dependant habitat diversity at the margins of the Kotoń mire is similar to the zone KT-2, with some signal of possible reedbed development (<i>Glyceria</i> cf. <i>maxima</i>) and episodes of exposed wet mud of the lake bottom (<i>Eleocharis ovata</i>), at least at some marginal parts of the waterbody.</p> <p>Pure arctic-alpine flora becomes absent in this depth interval probably because of the warming climatic conditions and/or competition for light, however, some indicators of dry and open habitats around the Kotoń basin continue to occur sporadically (<i>Picris hieracioides</i>).</p> <p>At the very beginning of the KT-4 stage, a short disappearance of Bryopsida can be noticed, but soon they grow back in number showing also a distinct change in composition: previously predominating <i>Calliergon giganteum</i> becomes replaced by <i>Sarmentypnum exanullatum</i> (up to 100% of Bryopsida abundance) (Figure 3). A presence of this acidophilus moss species may suggest the transition of the Kotoń mire towards the moderately rich fen (Hájek et al. 2006). Additionally, in the upper part of the substage KT-4b, there is a growing proportion of <i>Aulacomnium palustre</i> and <i>Helodium blandowii</i>, which may reflect the occurrence of some drier (elevated) stands like small hummocks within the fen. Changes in Bryopsida composition could be caused by the autogenic succession and blocking of income of calcium-rich groundwater by increasing thickness of peat layer. A process of autogenic succession is also reflected by occurrences of species growing in waterlogged conditions as <i>Carex rostrata</i> and <i>Menyanthes trifoliata</i>. The occurrence of trees and shrubs in the fen vicinity, at the beginning represented by <i>Betula nana</i> and <i>Betula pubescens</i> in the zone KT-4a and later also by <i>Pinus sylvestris</i> and <i>Salix</i> sp. in zone KT-4b, could be related to the warming climate. Additionally, increased heterogeneity of water-logged conditions could enhance the spreading of <i>Betula nana</i> and <i>Betula pubescens</i> deeper into the fen area (Brock et al. 1989; Ejankowski 2008). In the substage KT-4a some more heliophilous representatives of fresh and moist habitats (<i>Linaria</i> sp., <i>Taraxacum</i> sp.) occurred only sporadically, whereas in the subzone KT-4b open-spaces and tundra presence around Kotoń fen were not signalized anymore. On the other hand, the absence of heliophilous plants in the macrofossil record at this stage can be attributed to the lack of water transport to the fen, not the direct disappearance of dry habitats around the Kotoń fen. A similar explanation should be considered in case of a complete</p>

(Continued)

Table 2. (Continued)

Depth and age range of the stage	Description (see also Figures 2–4)
	<p>decline of <i>Alchemilla</i> sp. In the KT-4 zone, <i>Hieracium</i> cf. <i>murorum</i> again co-occurred with spreading of trees.</p> <p>Further climate amelioration and/or decrease of water level in the Kotoń mire during the stage KT-4b allowed for expansion of <i>Pinus sylvestris</i> and possibly other Coniferae species, although the number of their macrofossils found is small and it is not clear whether well-developed birch-pine boreal forest spread widely in the mire's surroundings. Macrofossils of <i>Juniperus communis</i> and <i>Rubus saxatilis</i>, species nowadays occurring in the shrub layer of the <i>Pinus sylvestris</i> light taiga of boreal zone, were also found. The vegetation of the moderately rich fen was continuously composed of Bryopsida, sedges (predominating <i>Carex diandra</i> and <i>Carex rostrata</i>), <i>Menyanthes trifoliata</i> as well as <i>Betula nana</i> and sporadically <i>Epilobium palustre</i>. In the vicinity of the fen, <i>Urtica dioica</i> and <i>Salix</i> sp. used to grow.</p>

Despite their rarity across Europe, localities with the late glacial deposits in which GI-1d/Older Dryas was distinguished based on absolute chronology and reflected in pollen and/or plant macrofossil data represent various topographical settings and palaeoenvironmental conditions. In the central-western part of the Polish Lowlands, GI-1d/Older Dryas was recognized as a time of the main dune formation stage, replacing the earlier pedogenic processes of GI-1e/ Bølling climate amelioration (Moska et al. 2022) (Figure 4). In the sediments of small depressions developed within cover sand ridge near Rieme (NW Belgium), the GI-1d /Older Dryas was characterized by ceasing of organic material deposition and inserts of sand overblown to the depressions by wind as a result of surface erosion in an open landscape (Bos et al. 2013) (Figure 4). On the contrary, during GI-1e /Bølling and GI-1c /Allerød climatic oscillations these depressions experienced increase in the groundwater level probably related to permafrost thawing.

Bølling-Older Dryas-Allerød sequence (corresponding to GI-1e, GI-1d and GI-1c, respectively) was also distinctively recorded in the other NW Belgium site, Moervaart palaeo-lake (Bos et al. 2017) (Figure 4). In this sequence, Bølling was characterized by a development (due to rise in the groundwater level) of a calcareous and mesotrophic shallow lake fringed with swamps and surrounded by a dwarf shrub tundra. Older Dryas deposits revealed shallowing of the lake and a transition to a swamp, surrounded by a grass-steppe tundra landscape. Early Allerød lacustrine sediments of Moervaart lake documented a lake deepening, boreal birch forests development, soil formation and occurrence of more diverse vegetation and habitats.

In case of deposits of Gerzensee lake (603 m a.s.l.) located in the Swiss Plateau region, the chronology was based on the correlation of oxygen isotope record with those of NGRIP (Van Raden et al. 2013) and assigned ages according to GICC-05 time scale, as years BP (Ammann et al. 2013). The Older Dryas (GI-1d) was reflected only as a minor increase on herb curves in pollen profiles, related to re-expansion of stepic conditions, and it was identified as the Aegelsee Oscillation (Ammann et al. 2013).

In the Carpathians in Romania, sites with calibrated age scales, pollen and macrofossil data have been available for correlation with the GRIP oxygen isotope profile (Feurdean et al. 2007; Feurdean and Bennike 2004). For example, in Preluca Tiganului (730 m a.s.l.) (Feurdean and Bennike 2004), a small infilled former volcanic crater lake, during ca. 14,100–13,800 cal BP an episode of drying and cooling

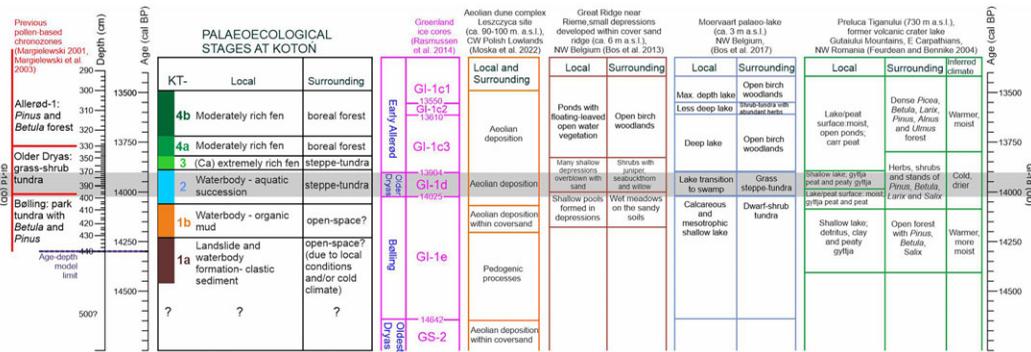


Figure 4. Stages of the palaeoecological development inferred for the Kotoń landslide fen deposits (500–300 cm depth interval) in correlation with previous pollen-based chronozones of Kotoń, Greenland ice cores event stratigraphy and stages of local and regional palaeoenvironmental development from various localities across Europe in which correlation with Greenland ice cores was used. The shaded area shows time range of the GI-1d/Older Dryas (OD) climatic oscillation.

correlated with Greenland ice cores, show distinct similarities but also differences. In case of all presented sites, during GI-1d/Older Dryas climatic oscillation vegetation of the surrounding areas was characterized by open-space habitats with herbs, shrubs and sparse tree stands, e.g. steppe-tundra, reflecting the cold and dry climatic conditions (Figure 4). There is also a consistency in occurrence of a shallowing process of the palaeo-lakes: during the Kotoń palaeoecological stage KT-2 an overgrowing of the waterbody was recognised, similarly to Moervaart palaeo-lake (transition to swamp) and Preluca Tiganului crater lake (decreasing water level, however with some episode of re-flooding) (Figure 4). Although for the other localities this process was attributed to the dry climatic conditions, in case of Kotoń site, the role of autogenic succession has to be considered as a main factor of the waterbody terrestrialization. Another difference is that no influence from the aeolian activity was detected in the Kotoń deposits as it was established for the Leszczyca or Rieme sites (Figure 4), possibly due to substantially different depositional environments (dunes/sand ridges of the lowlands vs landslide lake/fen of the mountains). During the proceeding Allerød climatic warming (GI-1c) and establishment of the boreal forest dominated by *Betula* and conifers (*Pinus*, *Larix*, *Picea*), the evolution of the mentioned sites differs according to the local hydrological regime (Figure 4). In case of Rieme and Moervaart the stage of a deeper waterbody reappears, whereas in case of Kotoń and Preluca Tiganului the shallow waterbodies of the Older Dryas stage overgrow further with vegetation and turn into the mires, possibly with some open-water pools preserved.

To sum up, despite the fact that the influence of GI-1d/Older Dryas climate cooling on the surrounding and regional vegetation was recognised for the Kotoń KT-2 deposits, in case of local vegetation and palaeohydrological changes more detail multi-proxy research is necessary to distinguish the climatic impact from the autogenic succession.

Conclusions

1. Four palaeoecological stages of development were determined for the Kotoń landslide fen deposits between ca. 14,600–13,500 cal BP showing the agreement with the earlier pollen division of the Kotoń deposits and with the extraregional chronology of the Greenland ice cores. Stage KT-1 (from ca. 14,240 ± 103 to > ca. 14,070 ± 72 cal BP, > ca. 170 years; GI-1e/Bølling and possibly the GS-2/Oldest Dryas) was characterized by the occurrence of a poor-in-vegetation waterbody with prevailing clastic sedimentation in the presumably open-space surrounding (caused by local landslide conditions and/or cold climate). Stage KT-2 (from ca. 14,070 ± 72 to

ca. 13,900 ± 56 cal BP, >ca. 170 years, the GI-1d/Older Dryas) was represented by a gyttja-like deposits of oligo-mesotrophic waterbody with vegetation dominated by Characeae meadows, *Sarmentypnum trichophyllum* and sedges, probably surrounded by the steppe-tundra habitats. Stage KT-3 (from ca. 13,900 ± 56 to ca. 13,820 ± 68 cal BP, ca. 80 years; the transition from the GI-1d /Older Dryas to GI-1c/Allerød) documented waterbody overgrowing as a result of natural autogenic succession and a change into (calcareous) extremely rich fen predominated by calciphilous Bryopsida species. Stage KT-4 (from ca. 13,820 ± 68 to ca. 13,500 ± 115, ca. 320 years; GI-1c/Allerød) documented the birch-pine boreal forest development caused by climate warming and the transition to the moderately rich fen probably due to moss fen peat accumulation (reduced access to the calcium-rich groundwater).

2. Despite their rarity across Europe, localities with the late glacial deposits in which GI-1d/Older Dryas was distinguished based on absolute chronology and reflected in pollen and/or plant macrofossil data represent various topographical settings and palaeoenvironmental conditions. In all presented sites, during the Older Dryas climatic oscillation vegetation of the surrounding areas was characterized by open-space habitats with herbs, shrubs and sparse tree stands, e.g. steppe-tundra, reflecting the cold and dry climatic conditions. Locally, some of the sites (including Kotoń) experienced a shallowing of the existing palaeo-waterbodies. Although for the other localities this process was attributed to the dry climatic conditions, in case of Kotoń site the role of autogenic succession has to be considered as a main factor of the waterbody terrestrialization. Even though the influence of GI-1d/Older Dryas climate cooling on the surrounding and regional vegetation was recognised for the Kotoń KT-2 deposits, in case of local vegetation and palaeohydrological changes more detail multi-proxy research is necessary to distinguish the climatic impact from the autogenic succession.

Supplementary material. To view supplementary material for this article, please visit <https://doi.org/10.1017/RDC.2025.10122>

Acknowledgments. This study was supported with funds from the National Science Centre, Poland, grant No. 2020/39/O/ST10/03504 (2021–2025). Bryopsida identification and interpretation conducted within this study was supported with funds from the Polish National Agency for Academic Exchange within a NAWA Preludium Bis 2 foreign doctoral internship programme (BPN/PRE/2022/1/00033/U/00001). We are grateful to the Doctoral School of Natural and Agricultural Sciences in Kraków for the opportunity to conduct the research project as a PhD thesis. We thank Prof. Andrzej Obidowicz (W. Szafer Institute of Botany, Polish Academy of Sciences) for pollen analysis carried out during previous studies, MSc Eng. Andrzej Kalemba (Institute of Nature Conservation Polish Academy of Sciences) for his help with field works, as well as Prof. Krzysztof Lipka from the Agriculture University in Kraków, Poland, for peat type analysis. We thank also Dr. Lars Hedenäs (Swedish Museum of Natural History, Stockholm, Sweden) for help in identification of *Sarmentypnum trichophyllum* and Doc. RNDr. Vítězslav Plášek (University of Ostrava, Czech Republic) for help in identification of *Hygrohypnum molle* s.lat., *Hygrohypnum ochraceum* and *Kindbergia* cf. *praelonga*. We sincerely thank the anonymous reviewers for their thorough and invaluable comments that led us to greatly improve our manuscript.

Declaration of competing interests. The authors have no competing interests to declare that are relevant to the content of this article.

References

- Aalto M (1970) Potamogetonaceae fruits I. Recent and subfossil endocarps of the Fennoscandian species. *Acta Botanica Fennica* **88**, 1–85.
- Ammann B, van Leeuwen JFN, van der Knaap WO, Lischke H, Heiri O and Tinner W (2013) Vegetation responses to rapid warming and to minor climatic fluctuations during the Late-Glacial Interstadial (GI-1) at Gerzensee (Switzerland). *Palaeogeography, Palaeoclimatology, Palaeoecology* **391**, 40–59. <https://doi.org/10.1016/j.palaeo.2012.07.010>.
- Anderberg A-L (1994) *Atlas of seeds and small fruits of Northwest-European plant species with morphological descriptions. Part 4. Resedaceae–Umbelliferae*. Stockholm: Swedish Museum of Natural History.
- Baumgart-Kotarba M and Kotarba A (1993) Późnoglacialne i holocenijskie osady z Czarnego Stawu Gąsienicowego w Tatrach. In Kotarba A (ed), *Dokumentacja Geograficzna. Z badań fizyczno-geograficznych w Tatrach.*, Vol. **4–5**. Warszawa: Instytut Geografii i Przestrzennego Zagospodarowania PAN, 9–30. (in Polish)

- Baumgart-Kotarba M, Kotarba A and Obidowicz A (1994) Kontrowersje datowań radiowęglowych i wyników badań palinologicznych na przykładzie osadów z Tatr Polskich. In *Zeszyty Naukowe Politechniki Śląskiej, Geochronometria 10*. Gliwice: Wydawnictwo Politechniki Śląskiej, 191–205. (in Polish)
- Bennett KD (1996) Determination of the number of zones in a biostratigraphical sequence. *New Phytologist* **132**, 155–170.
- Berggren G (1969) *Atlas of seeds and small fruits of Northwest-European plant species with morphological descriptions. Part 2: Cyperaceae*. Stockholm: Swedish Natural Science Research Council.
- Berggren G (1981) *Atlas of seeds and small fruits of Northwest-European plant species with morphological descriptions. Part 3: Salicaceae - Cruciferae*. Stockholm: Swedish Museum of Natural History.
- Birks HH (2013) Plant macrofossil introduction. In Elias SA and Mock CJ (eds), *Encyclopedia of Quaternary Science*, Second Edn. Amsterdam: Elsevier, 593–612. <https://doi.org/10.1016/B978-0-444-53643-3.00203-X>.
- Björck S, Walker MJC, Cwynar LC, Johnsen SJ, Knudsen K-L, Lowe JJ and Wohlfarth B (1998) An event stratigraphy for the Last Termination in the North Atlantic region based on the Greenland ice-core record: a proposal by the INTIMATE group. *Journal of Quaternary Science* **13**(4), 283–292. [https://doi.org/10.1002/\(SICI\)1099-1417\(199807/08\)13:4<283::AID-JQS386>3.0.CO;2-A](https://doi.org/10.1002/(SICI)1099-1417(199807/08)13:4<283::AID-JQS386>3.0.CO;2-A).
- Borsukevych L (2013) The distribution, ecology and phytosociology of rare *Potamogeton* species in central part of western Ukraine. In Dyguś KH (ed) *Natural Human Environment: Dangers, protection, education: Monograph*. Warszawa: Oficyna Wydawnicza Wyższej Szkoły Ekologii i Zarządzania, 123–134.
- Bos JAA, De Smedt P, Demiddele H, Hoek WZ, Langohr R, Marcelino V, Van Asch N, Van Damme D, Van der Meer T, Verniers J, Boeckx P, Boudin M, Court-Picon M, Finke P, Gelorini V, Gobert S, Heiri O, Martens K, Mostaert F, Serbruyns L, Van Strydonck M and Crombé P (2017) Multiple oscillations during the Lateglacial as recorded in a multi-proxy, high-resolution record of the Moervaart palaeolake (NW Belgium). *Quaternary Science Reviews* **162**, 26–41. <https://doi.org/10.1016/j.quascirev.2017.02.005>.
- Bos JAA, Verbruggen F, Engels S and Crombé P (2013) The influence of environmental changes on local and regional vegetation patterns at Rieme (NW Belgium): Implications for Final Palaeolithic habitation. *Vegetation History and Archaeobotany* **22**, 17–38. <https://doi.org/10.1007/s00334-012-0356-0>.
- Brock TCM, Jongerhuis R, Van Der Molen PC and Ran ETH (1989) A comparison of the history and present state of an *Alnus glutinosa* and a *Betula pubescens* dominated patch of wetland forest in the nature reserve 'Het Molenven', The Netherlands. *Acta Bot. Neerl* **38**(4), 425–437.
- Bronk Ramsey C (2009) Bayesian analysis of radiocarbon dates. *Radiocarbon* **51**(1), 337–360. <https://doi.org/10.1017/s0033822200033865>.
- Bronk Ramsey C (2021) Oxcal version 4.4.4. <https://c14.arch.ox.ac.uk>.
- Burdakiewicz JM, Szykiewicz A and Malkiewicz M (2007) Palaeoenvironmental setting of the Late Paleolithic sites in Kopanica Valley. In Kobusiewicz M and Kabaciński J (eds), *Studies in the Final Paleolithic Settlement of the Great European Plain*. Poznań: Institute of Archeology and Ethnology Polish Academy of Sciences, Branch Poznań and Poznań Prehistoric Society, 67–85.
- Cappers RTJ, Bekker RM and Jans JEA (2012) *Digital seed atlas of the Netherlands/ Digitale Zadenatlas van Nederland*, 2nd edn. Groningen: Barkhuis Publishing & Groningen University Library. <https://www.plantatlas.eu/search/database>.
- De Klerk P (2004) Confusing concepts in Lateglacial stratigraphy and geochronology: Origin, consequences, conclusions (with special emphasis on the type locality Bøllingsø). *Review of Palaeobotany and Palynology* **129**(4), 265–298. <https://doi.org/10.1016/j.revpalbo.2004.02.006>.
- Dítě D, Hájek M, Svitková I, Košťuhová A, Šoltés R and Kliment J (2018) Glacial-relict symptoms in the Western Carpathian flora. *Folia Geobotanica* **53**(3), 277–300. <https://doi.org/10.1007/s12224-018-9321-8>.
- Dítě D and Pukajová D (2003) *Carex magellanica* subsp. *irrigua* - A new taxon in the Western Carpathians. *Biologia - Section Botany* **58**(4), 791–796.
- Drzymulska D (2010) Historia torfowiska Taboły (Puszcza Knyszyńska) w późnym glacie i holocenie. *Woda-Środowisko-Obszary Wiejskie* **10**, 21–31. (in Polish)
- Dzieduszyńska DA and Forysiak J (2019) Chronostratigraphy of the Late Vistulian in Central Poland and the correlation with Vistulian glacial phases. *Studia Quaternaria* **36**(2), 137–145. <https://doi.org/10.24425/sq.2019.126385>.
- Ejankowski W (2008) Effect of waterlogging on regeneration in the dwarf birch (*Betula nana*). *Biologia* **63**(5), 670–676. <https://doi.org/10.2478/s11756-008-0126-8>.
- Elkington TT (1971) *Dryas octopetala* L. Biological Flora of the British Isles No. 124. *Journal of Ecology* **59**, 887–905.
- Feurdean A and Bennike O (2004) Late Quaternary palaeoecological and palaeoclimatological reconstruction in the Gutaiului Mountains, northwest Romania. *Journal of Quaternary Science* **19**(8), 809–827. <https://doi.org/10.1002/jqs.872>.
- Feurdean A, Wohlfarth B, Björckman L, Tantau I, Bennike O, Willis KJ, Farcas S and Robertsson AM (2007) The influence of refugial population on Lateglacial and early Holocene vegetational changes in Romania. *Review of Palaeobotany and Palynology* **145**(3–4), 305–320. <https://doi.org/10.1016/j.revpalbo.2006.12.004>.
- Gałka M and Sznal M (2013) Late Glacial and Early Holocene development of lakes in northeastern Poland in view of plant macrofossil analyses. *Quaternary International* **292**, 124–135. <https://doi.org/10.1016/j.quaint.2012.11.014>.
- Goslar T, Ralska-Jasiewiczowa M, Starkel L, Demske D, Kuc T, Łącka B, Szeroczyńska K, Wicik B and Więckowski K (1998) Discussion of the Late-Glacial recorded in the Lake Gościąg sediments. In Ralska-Jasiewiczowa M, Goslar T, Madeyska E, and Starkel L (eds), *Lake Gościąg, Central Poland. A monographic study. Part 1*. Kraków: W. Szafer Institute of Botany, Polish Academy of Sciences, 171–175.

- Grimm EC (1987) CONISS: A FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers and Geosciences* **13**(1), 13–35. [https://doi.org/10.1016/0098-3004\(87\)90022-7](https://doi.org/10.1016/0098-3004(87)90022-7).
- Grimm EC (1991) *TILIA and TILIA graph*. Springfield: Illinois State Museum.
- Hájek M, Horskák M, Hájková P and Dítě D (2006) Habitat diversity of central European fens in relation to environmental gradients and an effort to standardise fen terminology in ecological studies. *Perspectives in Plant Ecology, Evolution and Systematics* **8**(2), 97–114. <https://doi.org/10.1016/j.ppees.2006.08.002>.
- Harmata K (1987) Late-Glacial and Holocene history of vegetation at Roztoki and Tarnowiec near Jasło (Jasło-Sanok Depression). *Acta Palaeobotanica* **27**(1), 43–65.
- Heiri O, Lotter A and Lemcke G (2001) Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology* **125**(2), 101–110. <https://doi.org/10.1023/A:1008119611481>.
- Hrivnák R, Kochjarová J and Ofaheľová H (2011) Vegetation of the aquatic and marshland habitats in the Orava region, including the first records of *Potametum alpini*, *Potametum zizii* and *Ranunculo-Juncetum bulbosi* in the territory of Slovakia. *Biologia* **66**(4), 626–637. <https://doi.org/10.2478/s11756-011-0060-z>.
- Iversen J (1954) The late-glacial flora of Denmark and its relation to climate and soil. *Danmarks Geologiske Undersøgelser II. Række* **80**, 87–119.
- Juggins S (2022) Rioja: Analysis of quaternary science data. R package version 1.0-5, <https://cran.r-project.org/package=rjoja>.
- Kats NY, Kats SV and Kiptiani MG (1965) *Atlas and keys of fruits and seeds occurring in the Quaternary deposits of the USSR*. Moscow: Nauka. (in Russian)
- Kolaczek P, Gałka M, Karpińska-Kolaczek M and Lutyńska M (2015) Late Pleniglacial and Late Glacial lake-mire transformations in south-eastern Poland reflected in aquatic and wetland vegetation changes. *Quaternary International* **388**, 39–50. <https://doi.org/10.1016/j.quaint.2014.04.042>.
- Koperowa W (1961) Późnoglacialna i holoceńska historia roślinności Kotliny Nowotarskiej. *Acta Palaeobotanica* **2**(3), 3–57. (in Polish)
- Körber-Grohne U (1964) Bestimmungsschlüssel für subfossile Juncus- Samen und Gramineen- Früchte. In Haarnagel W (ed), *Probleme der Küstenforschung im Südlichen Nordseegebiet 7*. Hildesheim: August Lax, 1–47. (in German)
- Körber-Grohne U (1991) Identification key for subfossil Gramineae fruits. *Probleme der Küstenforschung im Südlichen Nordseegebiet* **18**, 169–234.
- Kowalewski G (2014) Alogeniczne i autogeniczne składowe zarosty jezior: hipoteza wahań poziomu wody Studia Limnologica et Telmatologica, Monographiae I. Poznań: Polskie Towarzystwo Limnologiczne: Bogucki Wydawnictwo Naukowe. (in Polish)
- Książkiewicz M (1972) Karpaty. In Pożaryski W (ed), *Budowa geologiczna Polski, part IV, Tektonika. vol. 3, Karpaty*. Warszawa: Wydawnictwo Geologiczne, 228. (in Polish)
- Książkiewicz M, Rączkowski W and Wójcik A (2016) *Szczegółowa Mapa Geologiczna Polski w skali 1:50000, Arkusz Osielec*. Warszawa: Ministerstwo Środowiska. (in Polish)
- Latałowa M and Nalepka D (1987) A study of the Late-Glacial and Holocene vegetational history of the Wolbrom area (Silesian-Cracovian Upland). *Acta Palaeobotanica*. 75–115.
- Lewandowska A, Milecka K, Niedzielski P, Czerwiński S and Gałka M (2023) Late Glacial development of lakes and wetland vegetation in a dune area in Central Poland. *Acta Palaeobotanica* **63**(1), 1–20. <https://doi.org/10.35535/acpa-2023-0001>.
- Litt T, Brauer A, Goslar T, Merkt J, Balaga K, Müller H, Ralska-Jasiewiczowa M, Stebich M and Negendank JFW (2001) Correlation and synchronisation of Lateglacial continental sequences in northern central Europe based on annually laminated lacustrine sediments. *Quaternary Science Reviews* **20**(11), 1233–1249. [https://doi.org/10.1016/S0277-3791\(00\)00149-9](https://doi.org/10.1016/S0277-3791(00)00149-9).
- Lotter AF, Eicher U, Siegenthaler U and Birks HJB (1992) Late-glacial climatic oscillations as recorded in Swiss lake sediments. *Journal of Quaternary Science* **7**, 187–204. <https://doi.org/10.1002/jqs.3390070302>.
- Lowe JJ, Rasmussen SO, Björck S, Hoek WZ, Steffensen JP, Walker MJC and Yu ZC (2008) Synchronisation of palaeoenvironmental events in the North Atlantic region during the Last Termination: a revised protocol recommended by the INTIMATE group. *Quaternary Science Reviews* **27**(1–2), 6–17. <https://doi.org/10.1016/j.quascirev.2007.09.016>.
- Lüth M (2019) *Mosses of Europe: a photographic flora. Volume 3*. Freiburg: Michael Lüth.
- Mangerud J, Andersen ST, Berglund BE and Donner JJ (1974) Quaternary stratigraphy of Norden, proposal for terminology and classification. *Boreas* **3**, 109–128.
- Margielewski W (2001) Rejestr zmian klimatycznych późnego glacialu i holocenu w obrębie torfowiska pod Kotoniem (Beskid Średni, Karpaty Zewnętrzne). *Przegląd Geologiczny* **49**(12), 1161–1166. (in Polish)
- Margielewski W (2018) Landslide fens as a sensitive indicator of paleoenvironmental changes since the Late Glacial: A case study of the Polish Western Carpathians. *Radiocarbon* **60**(4), 1199–1213. <https://doi.org/10.1017/RDC.2018.68>.
- Margielewski W, Michczyńska DJ, Buczek K, Michczyński A, Korzeń K and Obidowicz A (2022b) Towards the understanding of the present-day human impact on peatland deposits formed since the Late Glacial: a retrospective age-depth model of the Grel raised bog (Polish Inner Carpathians). *Radiocarbon* **64**(6), 1525–1543. <https://doi.org/10.1017/RDC.2022.62>.
- Margielewski W, Obidowicz A and Pelc S (2003) Late Glacial-Holocene peat bog on Kotoń Mt. and its significance for reconstruction of palaeoenvironment in the Western Outer Carpathians (Beskid Makowski Range, South Poland). *Folia Quaternaria* **74**, 35–56.

- Margielewski W, Obidowicz A, Zernitskaya V and Korzeń K (2022a) Late Glacial and Holocene palaeoenvironmental changes recorded in landslide fans deposits in the Polish Outer Western Carpathians (Southern Poland). *Quaternary International* **616**, 67–86. <https://doi.org/10.1016/J.QUAINT.2021.11.001>.
- Mauquoy D and van Geel B (2007) Mire and peat macros. In Elias SA (ed), *Encyclopedia of Quaternary Science, Volume 3*, 2nd edn. Amsterdam: Elsevier Science, 2315–2336. <https://doi.org/10.1016/B0-44-452747-8/00229-5>.
- Michczyński A, Kołaczek P, Margielewski W and Michczyńska D (2013) Radiocarbon age-depth modeling prevents misinterpretation of past vegetation dynamics: case study Wierchomla mire (Polish Outer Carpathians). *Radiocarbon* **55**(3–4), 1724–1734. https://doi.org/10.2458/azu_js_rc.55.16308.
- Mirek Z (2013) Altitudinal vegetation belts of the Western Carpathians. In Obidowicz A, Madeyska E, and Turner C (eds), *Postglacial history of vegetation in the Polish part of the Western Carpathians based on isopollen maps*. Kraków: W. Szafer Institute of Botany, Polish Academy of Sciences, 15–21.
- Mirek Z, Piękoś-Mirkowa H, Zając A and Zając M (2020) *Vascular plants of Poland. An annotated checklist*. Kraków: W. Szafer Institute of Botany, Polish Academy of Sciences.
- Moska P, Sokołowski RJ, Jary Z, Zieliński P, Raczyk J, Szymak A, Krawczyk M, Skurzyński J, Poręba G, Łopuch M and Tudyka K (2022) Stratigraphy of the Late Glacial and Holocene aeolian series in different sedimentary zones related to the Last Glacial maximum in Poland. *Quaternary International* **630**, 65–83. <https://doi.org/10.1016/j.quaint.2021.04.004>.
- Nalepka D (1994) The history of vegetation in the western part of Sandomierz Basin during the last 15 000 years. *Wiadomości Botaniczne* **38**(3/4), 95–105. (in Polish)
- Nalepka D (2005) Late Glacial and Holocene palaeoecological conditions and changes of vegetation cover under early farming activity in the south Kujawy region (central Poland). *Acta Palaeobotanica Supplement* **6**, 1–93.
- Novik A, Punning J-M and Zernitskaya V (2010) The development of Belarusian lakes during the Late Glacial and Holocene. *Estonian Journal of Earth Sciences* **59**(1), 63–79. <https://doi.org/10.3176/earth.2010.1.05>.
- Obidowicz A (1993) Wahania górnej granicy lasu w późnym plejstocenie i holocenie w Tatrach. In Kotarba A (ed), *Dokumentacja Geograficzna. Z badań fizyczno-geograficznych w Tatrach.*, Vol. **4–5**. Warszawa: Instytut Geografii i Przestrzennego Zagospodarowania PAN, 31–43. (in Polish)
- Obidowicz A (1996) A Late Glacial-Holocene history of the formation of vegetation belts in the Tatra Mts. *Acta Palaeobotanica* **36**(2), 159–206.
- Pladias – Database of the Czech Flora and Vegetation. www.pladias.cz
- Pełechaty M, Pełechata A and Pukacz A (2007) *Flora i roślinność ramienicowa na tle stanu trofii jezior Pojezierza Lubuskiego (Środkowo - zachodnia Polska)*. Poznań: Bogucki Wydawnictwo Naukowe. (in Polish)
- Ralska-Jasiewiczowa M, Demske D and van Geel B (1998) Late-Glacial vegetation history recorded in the Lake Gościąg sediments. In Ralska-Jasiewiczowa M, Goslar T, Madeyska E, and Starkel L (eds), *Lake Gościąg, Central Poland. A monographic study. Part 1*. Kraków: W. Szafer Institute of Botany, Polish Academy of Sciences, 128–143.
- R Core Team (2022) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria, <https://www.R-project.org/>.
- Rasmussen SO, Bigler M, Blockley SP, Blunier T, Buchardt SL, Clausen HB, Cvijanovic I, Dahl-Jensen D, Johnsen SJ, Fischer H, Gkinis V, Guillevic M, Hoek WZ, Lowe JJ, Pedro JB, Popp T, Seierstad IK, Steffensen JP, Svensson AM, Vallelonga P, Vinther BM, Walker MJC, Wheatley JJ and Winstrup M (2014) A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: Refining and extending the INTIMATE event stratigraphy. *Quaternary Science Reviews* **106**, 14–28. <https://doi.org/10.1016/j.quascirev.2014.09.007>.
- Reimer PJ, Austin WEN, Bard E, Bayliss A, Blackwell PG, Bronk Ramsey C, Butzin M, Cheng H, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Hajdas I, Heaton TJ, Hogg AG, Hughen KA, Kromer B, Manning SW, Muscheler R, Palmer JG, Pearson C, Van Der Plicht J, Reimer RW, Richards DA, Scott EM, Southon JR, Turney CSM, Wacker L, Adolphi F, Büntgen U, Capano M, Fahrni SM, Fogtmann-Schulz A, Friedrich R, Köhler P, Kudsk S, Miyake F, Olsen J, Reinig F, Sakamoto M, Sookdeo A and Talamo S (2020) The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). *Radiocarbon* **62**(4), 725–757. <https://doi.org/10.1017/RDC.2020.41>.
- Szymczyk A (2015) *Relacje między zespołami szczątków karpologicznych a współczesną roślinnością małych, płytkich zbiorników wodnych*. Katowice: Wydawnictwo Uniwersytetu Śląskiego. (in Polish)
- Tołpa S, Jasnowski M and Pałczyński A (1967) System genetyczny klasyfikacji torfów występujących w złożach Europy Środkowej. *Zeszyty Problemowe Postępów Nauk Rolniczych* **76**, 27–99. (in Polish)
- Tomczyk AM and Bednorz E (eds) (2022) *Atlas klimatu Polski (1991-2020)*. Poznań: Bogucki Wydawnictwo Naukowe. (in Polish)
- Van Raden UJ, Colombaroli D, Gilli A, Schwander J, Bernasconi SM, van Leeuwen J, Leuenberger M and Eicher U (2013) High-resolution late-glacial chronology for the Gerzensee lake record (Switzerland): $\delta^{18}O$ correlation between a Gerzensee-stack and NGRIP. *Palaeogeography, Palaeoclimatology, Palaeoecology* **391**, 13–24. <https://doi.org/10.1016/j.palaeo.2012.05.017>.
- Velichkevich F and Zastawniak E (2006) *Atlas of the Pleistocene vascular plant macrofossils of Central and Eastern Europe. Part 1: Pteridophytes and Monocotyledons*. Kraków: W. Szafer Institute of Botany, Polish Academy of Sciences.
- Velichkevich F and Zastawniak E (2008) *Atlas of the Pleistocene vascular plant macrofossils of Central and Eastern Europe. Part 2: Herbaceous Dicotyledones*. Kraków: W. Szafer Institute of Botany, Polish Academy of Sciences.
- Wasylikowa K (1964) Roślinność i klimat późnego glacjału w środkowej Polsce na podstawie badań w Witowie koło Łęczycy. *Biuletyn Peryglacjalny* **13**, 261–417. (in Polish)

- Watts WA (1980) Regional variation in the response of vegetation to Lateglacial climatic events in Europe. In Lowe JJ, Gray JM, and Robinson JE (eds), *Studies in the Late-glacial of North-west Europe*. Oxford: Pergamon Press, 205.
- Welten M (1982) Vegetationsgeschichtliche Untersuchungen in den westlichen Schweizer Alpen: Bern-Wallis. In *Denkschriften der Schweizerischen Naturforschenden Gesellschaft*, Vol. 95. Basel: Birkhäuser Verlag, 1–104. (in German)
- Wójcik A and Rączkowski W (1994) *Objaśnienia do szczegółowej mapy geologicznej Polski 1:50000, Arkusz Osielec*. Warszawa: Wydawnictwo Geologiczne, 1–63. (in Polish)
- Zarzycki K (2002) *Ecological indicator values of vascular plants of Poland*. Kraków: W. Szafer Institute of Botany, Polish Academy of Sciences.
- Zernitskaya V (1997) The evolution of lakes in the Poles'ye in the Late Glacial and Holocene. *Quaternary International* 41–42, 153–160. [https://doi.org/10.1016/S1040-6182\(96\)00047-X](https://doi.org/10.1016/S1040-6182(96)00047-X).

Cite this article: Pilch J, Margielewski W, Stachowicz-Rybka R, and Buczek K. The Bølling-Older Dryas-Allerød transition (ca. 14,600–13,500 cal BP) in the palaeoecological record of the Kotoń landslide fen (the Outer Western Carpathians, S Poland)—from the local to extraregional perspective. *Radiocarbon* 1–21. <https://doi.org/10.1017/RDC.2025.10122>

Supplementary Information to the Radiocarbon paper:

The Bølling-Older Dryas-Allerød transition (ca. 14,600–13,500 cal BP) in the palaeoecological record of the Kotoń landslide fen (the Outer Western Carpathians, S Poland) – from the local to extraregional perspective.

Jolanta Pilch, Włodzimierz Margielewski, Renata Stachowicz-Rybka, Krzysztof Buczek

See next page.

SI-Table 1 Detailed description of the loss on ignition, peat type, plant and animal macrofossils data from a depth 500–300 cm divided into four palaeoecological stages of the Kotoń fen development.

Depth and age range of the stage	Results of the loss on ignition analysis and peat type description (Figure 2)	Results of the plant macrofossil analysis (Figure 3)
KT-1a 500–431 cm, > ca. 14,240, ± 103 cal BP	Minerogenic sediment: silt with sand and debris admixtures, showing low values of LOI <5%.	A single seed of <i>Juncus</i> sp. and a fruit of <i>Alchemilla</i> sp. Several fruits and urticles of <i>Carex rostrata</i> , which are present closer to the upper boundary of this zone. A few fruits and seeds of <i>Scirpus sylvaticus</i> at similar depth to <i>Carex rostrata</i> . Almost continuous presence of a few leaves from Bryopsida mosses. Single occurrences of Characeae oospores at different depths, along with macrofossils of Ostracoda, <i>Daphnia</i> sp., <i>Simocephalus</i> sp., Oribatid mites and Chironomidae. The horizon at a depth of 435–431 cm is more abundant in macrofossils. Next to the numerous fruits of <i>Alchemilla</i> sp., it contains single macrofossils of <i>Valeriana simplicifolia/dioica</i> , <i>Carex rostrata</i> , <i>Carex</i> sp. trigonus (not presented in the macrofossil diagram), Ostracoda, Porifera and Oribatid mites. Moreover, there is a single fragment of charcoal.
KT-1b 431–405 cm, from ca. 14,240 ± 103 to ca. 14,070 ± 72 cal BP, ca. 170 years	This interval consists of a clayey silt with an increasing content of organic matter (5–8%) visible on the LOI curve.	This zone is also poor in macrofossils. At the lower boundary, a single fruit of Asteraceae was found, whereas at the upper boundary a single fruit of <i>Solidago virgaurea</i> appears. Near the lower and upper boundaries of this zone, some fruits of <i>Alchemilla</i> sp. also occur. A few diaspores of <i>Carex magellanica</i> are present, along with single fruits of <i>Carex diandra</i> and <i>Scirpus sylvaticus</i> . Aquatic plants are represented by one fruit of <i>Batrachium</i> sp. and a few Characeae oospores. Ostracoda shells occur in a distinctive number, along with sporadic ehippia of <i>Daphnia</i> sp., <i>Simocephalus</i> sp., <i>Ceriodaphnia</i> sp. and others. There is again a single fragment of charcoal.
KT-2 405–367.5 cm,	Minerogenic material (silt) still prevails in the sediment of this zone,	This zone is the most abundant in plant and animal macrofossils in the analysed 500–300 cm depth section. Among trees, shrubs and dwarf shrubs, there are the first sporadic occurrences of <i>Betula pubescens</i> , <i>Betula</i> sect. <i>Albae</i> and <i>Betula</i> sp. macrofossils and a single bud scale of Coniferae

<p>from ca. 14,070 ± 72 to ca. 13,900 ± 56 cal BP, ca. 170 years</p>	<p>however, the share of organic matter continues to increase upward (10–20%), resulting in more gyttja /organic mud-like deposits.</p>	<p>occurs. Fragments of leaves (undifferentiated) show continuous occurrence. It is not possible to attribute them exclusively to tree species, shrubs or dwarf shrubs.</p> <p>Plants of dry habitats are represented by a single seed of <i>Dianthus</i> sp., one fruit and one leaf of <i>Dryas octopetala</i>, a few seeds of <i>Androsace</i> cf. <i>chamaejasme</i> and Caryophyllaceae.</p> <p>In the group of plants of fresh and moist habitats Poaceae fruits show continuous presence and there are single macrofossil finds of <i>Potentilla</i> cf. <i>crantzii</i>, <i>Melandrium rubrum</i> and <i>Heracleum sphondylium</i>. <i>Alchemilla</i> sp. fruits appear in a large number and show continuous presence through the entire zone. There is a frequent presence of <i>Urtica dioica</i> fruits.</p> <p>Plants of mire habitat are dominated by abundantly occurring Bryopsida. Besides that, there is a large number of fruits and urticles of <i>Carex nigra</i> and <i>Carex rostrata</i>, less numerous <i>Carex magellanica</i> and least abundant <i>Carex diandra</i>. There is a frequent presence of macrofossils of <i>Valeriana simplicifolia/dioica</i>, <i>Ranunculus repens</i>. There are a few seeds and fruits of <i>Epilobium palustre</i> and <i>Scirpus sylvaticus</i>.</p> <p>Aquatic organisms are dominated by macrophytes represented by continuously present abundant oospores of Characeae and numerous fruits of <i>Batrachium</i> sp. and <i>Potamogeton alpinus</i>. Along with them, there are plenty of Ostracoda shells, <i>Daphnia</i> sp. and <i>Simocephalus</i> sp. ehippia (rarely also of <i>Ceriodaphnia</i> sp.), Porifera gemmules and <i>Plumatella</i> statoblast. Oribatid mites, Chironomidae and Trichoptera remains are also very abundant.</p> <p>Bryopsida group is dominated by <i>Sarmentypnum trichophyllum</i> (more than 90% of all Bryopsida) and secondarily there are some small abundances of <i>Philonotis calcarea</i>, <i>Sarmentypnum exannulatum</i>, <i>Aulacomnium palustre</i> continuing throughout the zone. <i>Hygrohypnum molle</i> s. lat. is also present in several samples, whereas <i>Scurio-hypnum reflexum</i>, <i>Kindbergia</i> cf. <i>praelonga</i>, <i>Rhizomnium punctatum</i>, <i>Hygrohypnum ochraceum</i>, <i>Plagmonium</i> cf. <i>ellipticum</i> and <i>Palustriella decipiens</i> show single occurrences.</p>
--	---	--

<p>KT-3 367.5–345 cm, from ca. 13,900 ± 56 to ca. 13,820 ± 68 cal BP, ca. 80 years</p>	<p>In this depth interval, a share of organic matter starts to predominate (20%–65%) and accumulated moss fen peat (<i>Bryalo-Parvocaricioni bryaleti</i>, Margielewski et al. 2003) receives only some admixture of minerogenic matter.</p>	<p>In this stage, apart from single occurrence of <i>Betula pubescens</i> and <i>Betula</i> sect. <i>Albae</i>, some fruits of <i>Betula nana</i> appear for the first time. Among plants of dry habitats, single fruit of <i>Hieracium</i> cf. <i>murorum</i> and <i>Picris hieracioides</i> occur. Moreover, there are also single macrofossils belonging to Poaceae, <i>Melandrium rubrum</i> and <i>Heracleum sphondylium</i>. <i>Alchemilla</i> sp. fruits continue to appear in a large number.</p> <p>Bryopsida stem fragments grow in number furtherly, still predominating plants of mire habitat. Diasporas of <i>Carex rostrata</i> and <i>Carex diandra</i> are also numerous, whereas those of <i>Carex nigra</i> again rise in number. There are some single finds of <i>Ranunculus repens</i>, <i>Valeriana simplicifolia/dioica</i>, <i>Caltha palustris</i>, <i>Eleocharis ovata</i> and <i>Glyceria</i> cf. <i>maxima</i>.</p> <p>Characeae oospores, in this zone, abruptly fall in number to only a few, similarly to the other aquatic organisms. Only one fruit of <i>Potamogeton alpinus</i> was found in this zone. <i>Daphnia</i> sp., Porifera and Oribatid mites, show almost continuous presence, but low abundance. <i>Simocephalus</i> sp., Ostracoda, <i>Plumatella</i> and Trichoptera are less frequent.</p> <p>Bryopsida composition becomes dominated by <i>Calliergon giganteum</i> (up to 90% of the total Bryopsida abundance) which at some depths decline at the expense of the other species: <i>Philonotis calcarea</i> and <i>Palustriella decipiens</i>. There is also a small proportion of <i>Ptychostomum pseudotriquetrum</i> and <i>Drepanocladus trifarius</i>.</p>
<p>KT-4a 345–322.5 cm, from ca. 13,820 ± 68 to ca. 13,720 ±</p>	<p>The first half of this zone shows LOI values at first decreasing from ca. 65% to ca. 30% in a result of minerogenic matter admixture to the woody alder peat (<i>Alnioni aneti</i> composed of Bryales pl.</p>	<p>Trees, shrubs and dwarf shrubs in this zone are predominated by numerous fruits of <i>Betula pubescens</i> (continuous occurrence) and less frequent <i>Betula nana</i>. Other macrofossils include <i>Betula</i> sect. <i>Nanae</i>, <i>Betula</i> sect. <i>Albae</i> and one Coniferae bud scale. Noticeably, fragments of leaves do not appear in this subzone.</p> <p>There are some single representatives of plants of dry, fresh and moist habitats: <i>Linaria</i> sp., <i>Hieracium</i> cf. <i>murorum</i>, Poaceae and <i>Taraxacum</i> sp. Fruits of <i>Alchemilla</i> sp. disappear in this zone. There is a single occurrence of <i>Urtica dioica</i> fruit.</p>

87, ca. 100 years	sp. and decomposed <i>Alnus</i> sp. wood, Margielewski et al. 2003).	<p>Number of <i>Carex rostrata</i> macrofossils increase greatly several times, whereas <i>Carex diandra</i> and <i>Carex nigra</i> show significantly lower number, although a constant occurrence. Stems fragments of Bryopsida are reduced in number at the beginning of the interval but later come back in a great abundance. The new-coming species is <i>Menyanthes trifoliata</i>, appearing in noticeable number of seeds and almost continuous occurrence. Moreover, there is a single occurrence of <i>Scirpus sylvaticus</i>.</p> <p>Among aquatic organisms, macrophytes (besides single Characeae oospore and <i>Potamogeton alpinus</i> fruit) are absent. There is almost a continuous presence of Ostracoda, <i>Daphnia</i> sp., <i>Simocephalus</i> sp., Oribatid mites, Chironomidae, and Trichoptera and more sporadic <i>Ceriodaphnia</i> sp. and Porifera, however all of them in much smaller amounts comparing to the zone KT-2.</p> <p>In Bryopsida composition, <i>Calliergon giganteum</i> becomes replaced by <i>Sarmentypnum exanullatum</i> (up to 100% of the total Bryopsida abundance).</p>
KT-4b 322.5–300 cm, from ca. 13,720 ± 87 to ca. 13,500 ± 115, ca. 220 years	<p>In the second half of the KT-4 zone, LOI curve starts rising again reaching values slightly over 85% as a result of almost pure uncontaminated moss fen peat accumulation (<i>Bryalo-Parvocaricioni bryaleti</i> composed mostly of Bryales pl. sp., sedges and <i>Menyanthes</i></p>	<p>The uppermost stage is characterized by a few fragments of <i>Pinus sylvestris</i> needles and Coniferae bud scales. <i>Betula pubescens</i> macroremains again grow in number, whereas those of <i>Betula nana</i> keep on a similar level. At a depth of 310–312.5 cm numerous fruits of <i>Salix</i> sp. were found. Moreover, there is one seed of <i>Juniperus communis</i> and one fruit of <i>Rubus saxatilis</i> present.</p> <p>Several Poaceae and <i>Urtica dioica</i> fruits are the only representatives of plants of fresh and moist habitats.</p> <p>Plants of mire habitats are still dominated by Bryopsida, and secondarily by <i>Carex rostrata</i> (decreasing in number) and <i>Carex diandra</i> (increased in number). <i>Menyanthes trifoliata</i> is still noticeably present almost throughout this entire subzone. Other taxa present include <i>Carex nigra</i> and <i>Epilobium palustre</i>. Aquatic animal taxa almost disappear in this zone. Only Oribatid mites show continuous and abundant presence.</p>

trifoliata, Margielewski
et al. 2003).

In Bryopsida composition, apart from the predominating *Sarmentypnum exanullatum* (up to 100% of the total Bryopsida abundance), in the upper part of this substage there is a growing proportion of *Aulacomnium palustre* and *Helodium blandowii*.