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Collective analysis of radiocarbon and luminescence dating results from fluvial deposits in central and southern Poland in the context of INTIMATE stratigraphy

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We describe a collective analysis of radiocarbon and luminescence dating results from fluvial palaeoenvironments in various Polish regions (lowlands, highlands, mountains, and their forelands) south of the Last Glacial Maximum line. The study used 484 radiocarbon and 130 luminescence dates, for which summed probability density distributions were constructed using the OxCal program. The analysis is juxtaposed against high-resolution INTIMATE stratigraphy. It demonstrates that discontinuous records of fluvial environmental responses in such analyses reveal significantly more detail than studies conducted at individual sites. A strong correlation was observed between peaks in the probability density functions (PDFs) of radiocarbon dates and interstadial periods. Conversely, accumulations of luminescence dates are correlated with stadial periods.

Key words: Poland, fluvial activity, ^{14}C and luminescence age determinations, probability density functions, 80–11.7 cal kBP.

INTRODUCTION

From previous studies of the fluvial palaeoenvironment on Polish territory, it is known that generally, during cold periods with sparse or no vegetation cover, increased delivery of mineral material to valley floors led to aggradation. Large flow fluctuations and a positive balance of alluvial material resulted in the development of braided or anastomosing channels (Marine Isotope Stages: MIS4, MIS2, MIS1) (Mol, 1997; Mol et al., 2000; van Huissteden et al., 2001). In warmer periods, when vegetation coverage increased, the delivery of material to river channels decreased, leading to the dominance of erosion processes in the valleys. Discharge regularization and a negative balance of alluvia favoured the development of meandering or anastomosing channels (MIS5a, warmer intervals of MIS3, MIS1, Bølling, Allerød) (van Huissteden et al., 2001; Starkel, 2003). However, changes in channel systems were not synchronous, as local factors such as changes in the erosional base, alluvial lithology, valley floor gradient, and others also influenced them. In the Younger Dryas (YD), both braided channels and large meandering channels existed (Starkel, 2003).

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Relatively warm periods provided more favourable conditions for the accumulation of organic sediments in valley bottoms.

From the data collected at individual fluvial sediment sites, it appears that none of them provides a complete record of environmental changes over long time spans (in the sense of thousands of years). Numerous palaeoclimatic changes during this period likely influenced erosion, associated with extreme events such as floods.

The question arises whether the fluvial palaeoenvironment can provide data with higher resolution than the framework of marine isotope stages. To answer this, the authors conducted a collective analysis of radiocarbon and luminescence dating results for river deposits in specific regions of Poland located south of the Last Glacial Maximum (LGM) line (Marks, 2002; Marks et al., 2022a, b). These regions have been extensively investigated for many years regarding the response of river systems to climate changes during the Late Pleistocene. The study aimed to compare these recorded data with high-resolution data from the North Greenland Ice Core Project (NGRIP) and INTIMATE stratigraphy – INTegration Ice core, MArine and TErrestrial records (Rasmussen et al., 2014). The goal was to ascertain whether a collective analysis of chronostratigraphic data from multiple, non-continuous profiles can provide a more precise reconstruction of fluvial environmental responses to global climate changes than analyses conducted at individual sites. Similar analyses have been the subject of past research in Poland, encompassing various types of deposits, time intervals, and regions (Michczyńska and Pazdur, 2004; Starkel et al., 2006, 2017; Michczyńska et al., 2007, 2022; Michczyńska and Hajdas, 2010; Gębica et al., 2015; Dzieduszyńska, 2017, 2019). Recently conducted comprehensive analysis of a set of radiocarbon and luminescence dates for the fluvial palaeoenvironment (Michczyńska et al., 2023) showed a very good correlation between analysed changes in fluvial environmental activity (recorded in alluvial lithofacies diversity and the topography of valley bottoms) and large-scale changes in climatic conditions recorded in the NGRIP core. In the current study, the authors examined records for specific regions: central Poland (Łódź region), the Holy Cross Mountains, the Subcarpathian Basins, and the Carpathians.

RESEARCH AREA AND TEMPORAL SCOPE

Comparative studies were conducted at sites situated in river valleys to the south of the maximum extent of the Vistula Glaciation (Last Glacial Maximum line). The research areas are situated in central (Łódź region – ŁR) and southeastern Poland: Holy Cross Mountains (HCM), Subcarpathian Basins (SCB), and Carpathians (Fig. 1). They are characterized by a diversity of geological structure, topography, and climatic conditions. During the Middle Pleistocene, these areas were shaped by the ice sheets of the Saalian and/or Elsterian glaciations (Mojski, 2005; Marks et al., 2016a; Marks, 2023). Subsequently, fluvial, weathering, slope, and aeolian processes dominated.

From the ŁR, data comes from the systems of the 2nd order river valleys of the middle section of the Warta, and the middle sections of the Pilica and Bzura rivers. From the HCM, dates are from the valleys of the Belnianka and Lubrzanka (4th order rivers), and Czarna Nida and Łagowica (3rd order rivers). From the Carpathians and the SCB, data comes from the valleys of the Vistula (1st order river), the San, Wisłoka and Dunajec (2nd order rivers), and the Wisłok (3rd order river).

Sites with documented absolute ages of deposits obtained through radiocarbon (^{14}C) and luminescence (Thermoluminescence – TL/Optically Stimulated Luminescence – OSL) dating were selected. Both methods date various sediment types, complementing each other. The radiocarbon method has a practical limitation to ~50 ky. The range of luminescence methods is broader.

The analysis encompassed sites with fluvial deposits dated within the range of 80 to 11.7 cal kBP. This interval covers the Early Vistulian (corresponding to Marine Isotope Stage MIS5a; ~85–71 kBP), Lower Plenivistulian (MIS4; 71–58 kBP), Middle Plenivistulian (MIS3; 57–29 kBP), and Upper Plenivistulian and Late Vistulian (MIS2, and lower part of MIS1; 29–11.7 kBP) periods (Lisiecki and Raymo, 2005; Railsback et al., 2015; Marks et al., 2016b). During the time frame investigated, the research areas were mostly part of a periglacial domain with diverse climatic conditions. MIS numerical boundary ages were used according to data from Lorraine Lisiecki's Home Page.

METHODS AND DATA ANALYSED

The analysis included dates ranging from 80 to 11.7 cal kBP compiled by the authors' team (Michczyńska et al., 2022; Dzieduszyńska et al., 2023 – see also Supplements for these publications and extensive literature for individual sites cited therein). For this study, the dataset was augmented with a few unpublished dates (see Acknowledgements), but it was narrowed down solely to the fluvial palaeoenvironment. The dated samples originated from locations within sedimentary profiles where significant changes in sedimentological records occurred. These locations included various indicators such as facies changes in river deposits, the base and top of organic layer sequences, and significant alterations in the composition of specific pollen taxa within palynological diagrams found within oxbow fills. Samples for radiocarbon dating were mainly taken precisely from such locations. Such preferential sampling for dating facilitates the identification of the temporal boundaries of climate/environmental changes recorded at the sites analysed and helps determine whether these changes were characteristic of a single site, had a local or regional nature, or perhaps an even broader extent.

Work on the dating database has been ongoing since 2017. The process was facilitated by the fact that the authors of this article have been working in the field for many years, conducting their own analyses of numerous sites, and are very familiar with the literature on site studies from various regions. The database primarily includes conventional radiocarbon dates, which have greater uncertainties than dates obtained using Accelerator Mass Spectrometry (AMS). As for luminescence dates, both thermoluminescence (TL) and optically stimulated luminescence (OSL) techniques were used.

A total of 484 radiocarbon and 130 luminescence dates were included in the analyses for this study. Utilizing the *OxCal v.4.4.4* software (Bronk Ramsey, 2009, 2017) and the latest *IntCal20* calibration curve (Reimer et al., 2020), PDFs were generated and compared to the INTIMATE stratigraphy (Rasmussen et al., 2014). INTIMATE event stratigraphy is based on sudden climate changes, so it is natural to compare the fluvial environment that responds to sudden climate changes with this stratigraphy.

PDF curves were generated by summing the probability distributions of individual dates. For radiocarbon dates, these were probability distributions of calibrated dates, while for luminescence dates, they were Gaussian distributions. This cumulative analysis approach incorporated comprehensive information about individual age determinations. The assumption was

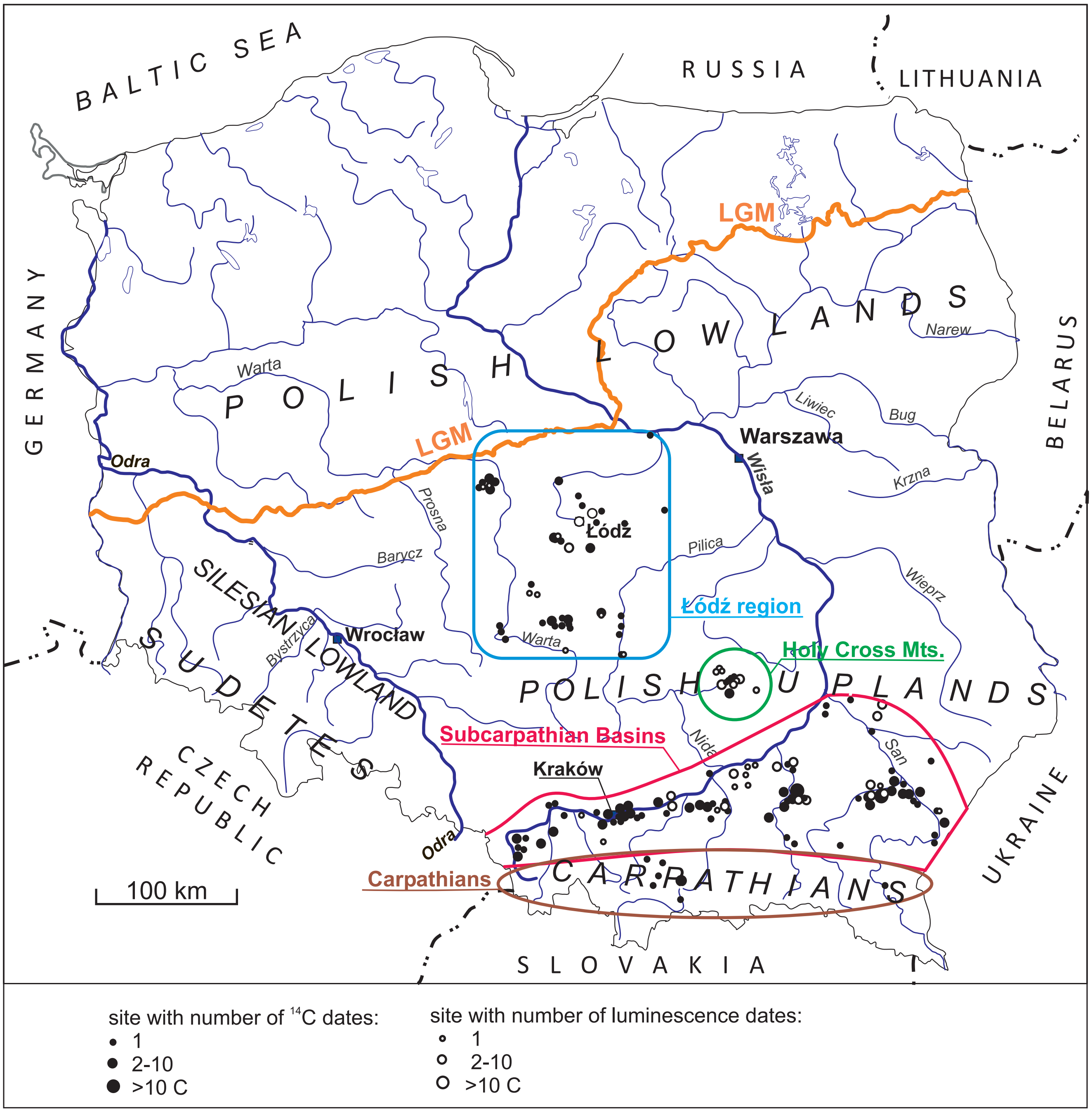

Fig. 1. Map of Poland with analysed sites marked

Last Glacial Maximum (LGM) limit is based on Marks et al. (2022a, b)

made that facies changes in the deposits examined were mostly responses to climatic impulses. When synchronous changes are observed at multiple sites, it results in a distinct peak in the PDF distributions, indicating the recording of a phenomenon that extends beyond the local scale (Michczyńska and Pazdur, 2004; Michczyńska et al., 2007).

A crucial focus lies in understanding how the fluvial systems in the regions examined reacted to global climate changes. To study global-scale changes, we used detailed archives from Greenland, such as the NGRIP ice core, categorized into Greenland Stadials (GS) and Greenland Interstadials (GI) within the INTIMATE stratigraphy (Rasmussen et al., 2014). Hence, the idea emerged to compare the PDF distributions of radiocarbon and luminescence dates with the oxygen curve from the NGRIP core and the INTIMATE stratigraphy (Rasmussen et al., 2014).

RESULTS

The graphical representation of analytical results is shown in Figure 2. This figure displays the summed probability distributions of radiocarbon and luminescence dates for the entire study area and individual regions. However, for the Carpathians, there are no luminescence dates in the compiled database.

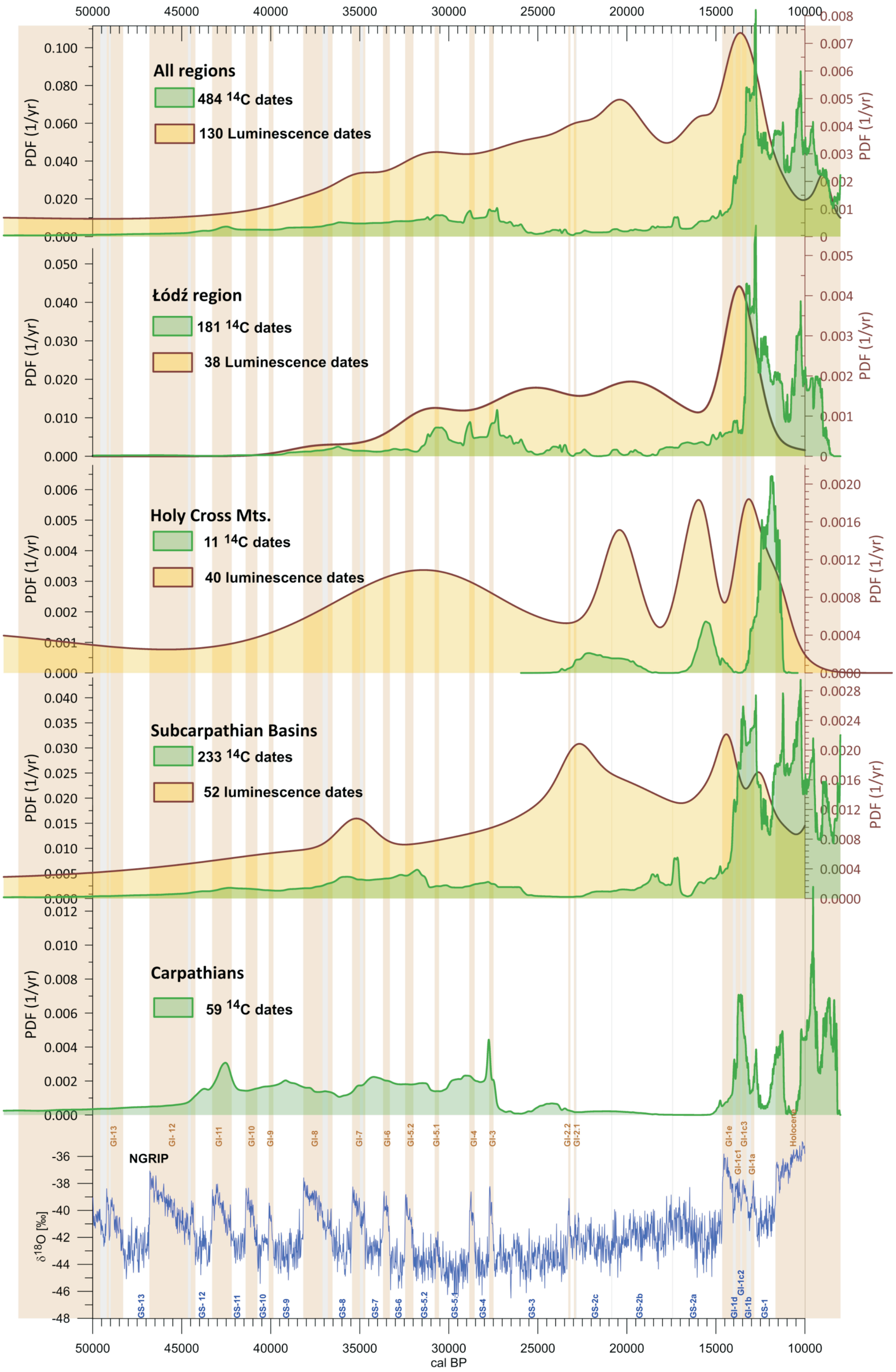

Fig. 2. Probability Density Distributions of luminescence and radiocarbon dates overlaid on the δ^{18}O curve from the NGRIP ice core and INTIMATE stratigraphy

The figure shows summary charts and divisions into individual regions; peaks in the luminescence date distribution are primarily correlated with cooling periods (GS), while radiocarbon dates are correlated with GIs/GSs and GSs/GIs transitions (interstadials indicated by beige vertical bars)

The collective analysis of age determinations revealed a strong correlation between the analysed changes in fluvial environmental activity, including variations in the lithofacial diversity of alluvium and valley floor topography, and large-scale changes in climatic conditions as documented in the NGRIP core (Fig. 2). Notably, the peaks in the probability distributions of radiocarbon dates correlate with the transitions between Greenland Stadials/Greenland Interstadials (GSs/GIs) and Greenland Interstadials/Greenland Stadials (GIs/GSs). By contrast, the accumulations of luminescence dates primarily coincide with periods correlated with the Greenland Stadials, indicating a potentially different response in dating materials to climatic variations.

In the case of radiocarbon dates, a significantly larger proportion of dates falls within the 15–10 cal kBP range. This can be attributed primarily to the greater availability of younger deposits, as well as the influence of climate warming and vegetation development following colder periods. As the impact of dates younger than 15 cal kBP is predominant, we narrowed the analyses down to the range of 15–50 cal kBP to provide a clearer view of older periods (refer to Figs. 3–6). Furthermore, for each of the regions, we showed the results of individual radiocarbon date calibration in the form of bars corresponding to 68.3% confidence intervals. We also included bars representing individual luminescence dates (date ± single standard deviation). This presentation format enhances the visibility of date accumulations, as summed distributions may obscure the details. In Figures 3–6, date clusters have been highlighted with rounded rectangles around the bars representing the 68.3% probability intervals of individual dates.

The dataset for the Łódź region comprises 38 luminescence dates and 181 ^{14}C dates (see Figs. 2 and 3). Showing them as

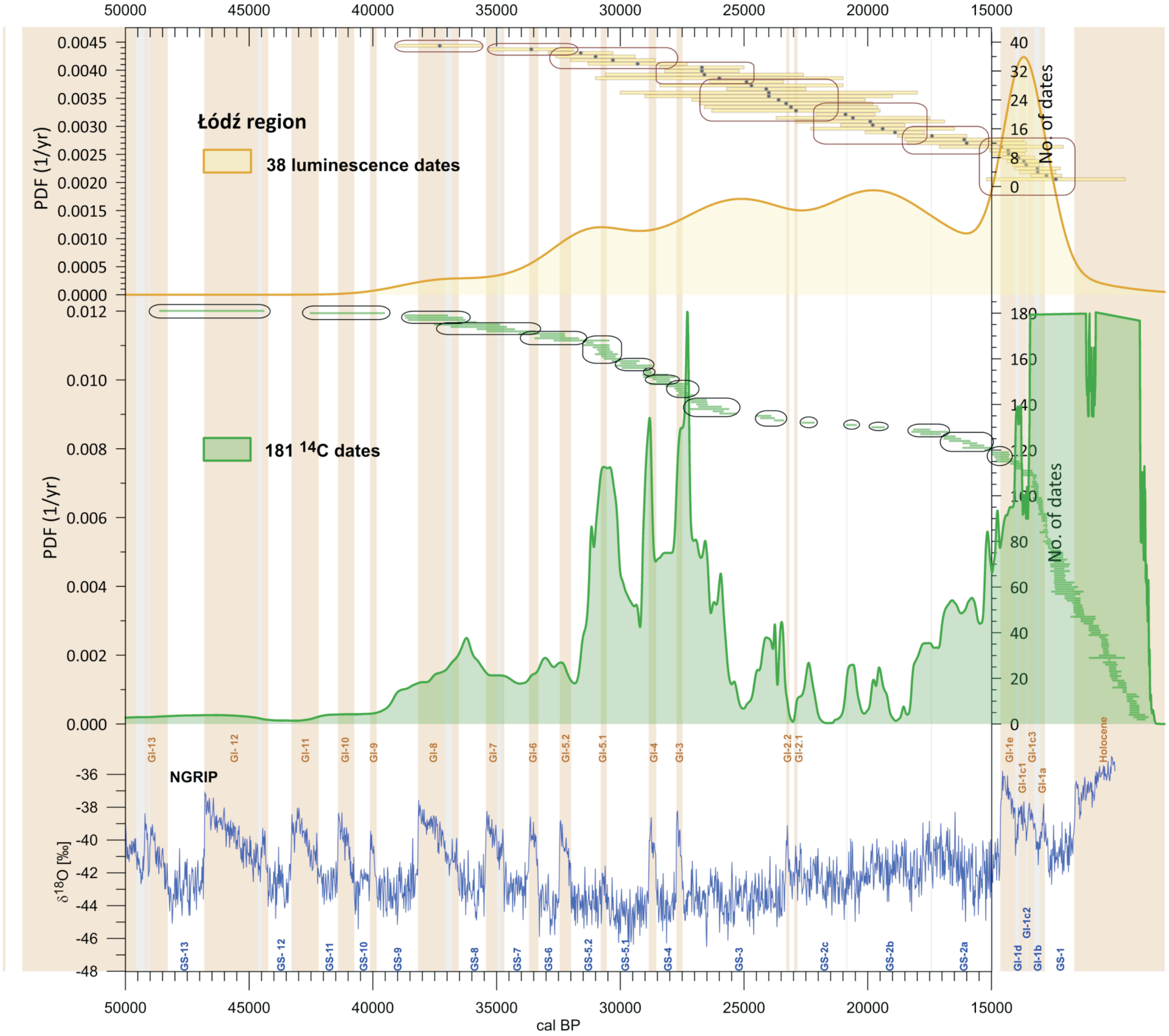

Fig. 3. Summed distributions of radiocarbon and luminescence dates for the Łódź region

Date clusters have been marked by rounded rectangles around the bars representing the 68.3% probability intervals of individual dates; notes: 1 – PDF chart for the ^{14}C dates for the range <15 cal kBP has been truncated at the top for clarity; 2 – for luminescence dates, in addition to the 68.3% probability bars, the medians were also marked with dots probability distributions alongside the INTIMATE stratigraphy yields the following observations:

- probability distribution of luminescence dates reveals 5 maxima, while representing these dates as bars (date ± single standard deviation) and allows for the identification of eight overlapping groups of dates;
- probability distribution of ^{14}C dates exhibits 11 maxima in the range 15–50 cal kBP, and representing these dates as bars (68.3% confidence intervals) enables the distinction of 17 (some overlapping) groups of dates.

The range 11.7–15 cal kBP has been extensively discussed by Dzieduszyńska et al. (2023), whose analysis revealed the clustering of ^{14}C dates at the following transitions: GS-2a/GI-1e; GI-1a/GS-1; and GS-1/Holocene. Moreover, each of the cooling periods within GI-1, namely GI-1d, GI-1c2 and GI-1b, was reflected in the form of peaks in the PDF curve.

For the Holy Cross Mountains in the time interval shown in Figure 4, there are 29 luminescence dates out of a total of 40, with only 11 ^{14}C dates available. Despite the limited number of ^{14}C dates, several observations can be made from the probability distribution of radiocarbon dates. Further insights can be gained by examining the calibration results represented as bars against the background of INTIMATE stratigraphy:

- oldest ^{14}C date is correlated with the transition of GI-2.1/GS-2c;
- next one aligns with GS-2c/GS-2b;
- a subsequent date coincides with GS-2a/GI-1;
- within GS-1, three date accumulations are noticeable: the first corresponding to the GI-1a/GS-1 boundary, the next to the middle of GS-1, and the final one to the GS-1/Holocene transition.

In contrast, the cumulative distribution of luminescence dates reveals four peaks (one older than 50 cal kBP). When these dates are represented as bars with marked mean values, they can be divided into seven subgroups, which, starting from the oldest, include successively 3 dates, 5 dates, 7 dates, 5 dates, 4 dates, 3 dates, and 2 dates.

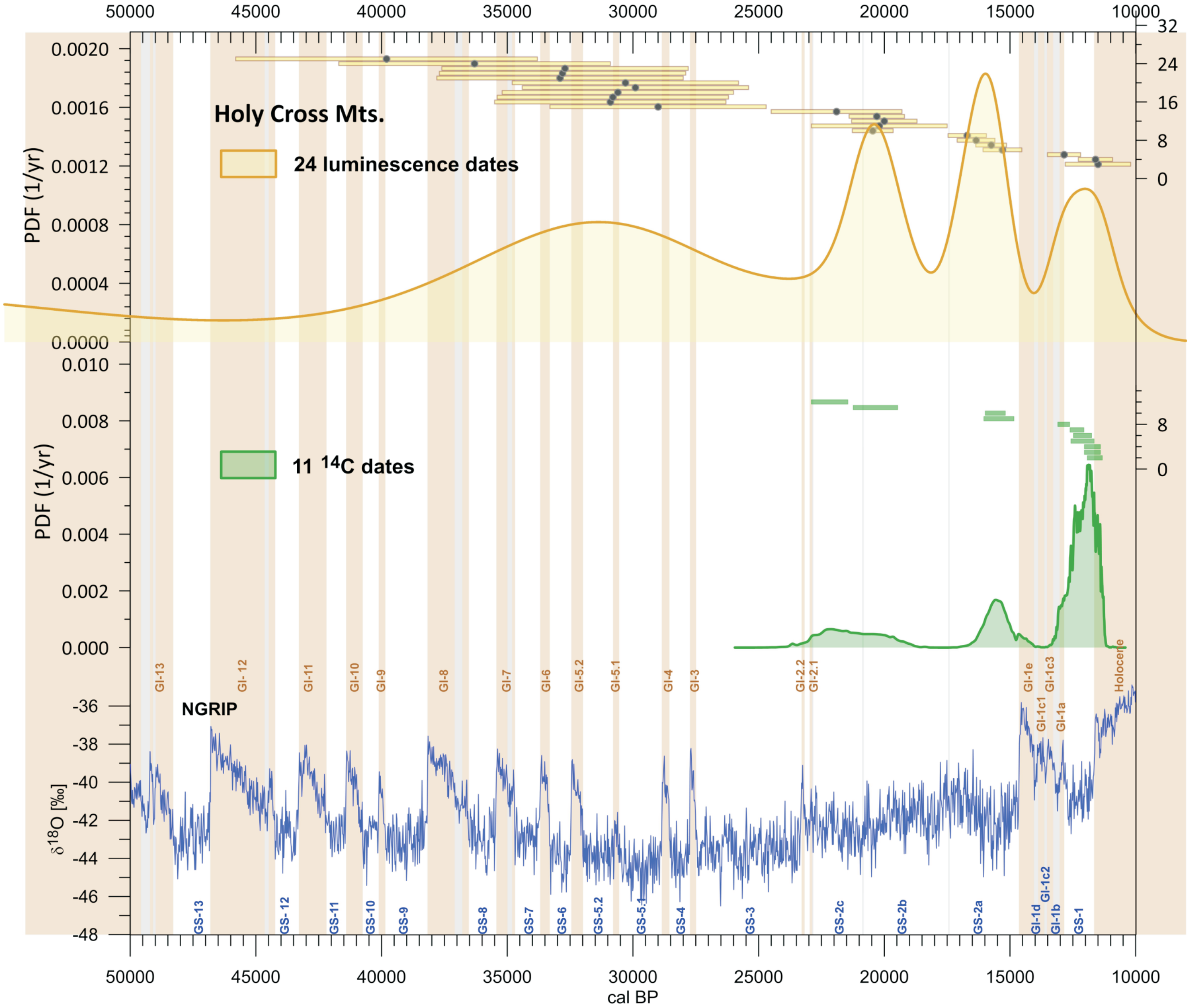

Fig. 4. Summed distributions of radiocarbon and luminescence dates for the Holy Cross Mountains region

Date clusters have been marked by rounded rectangles around the bars representing the 68.3% probability intervals of individual dates; PDF chart for the ^{14}C dates for the range <15 cal kBP has been truncated at the top for clarity

The dataset for the Subcarpathian Basins region consists of 44 luminescence dates and 233 ^{14}C dates (see Figs. 2 and 5). Their presentation in the form of probability distributions against the background of INTIMATE stratigraphy allows for the following observations:

- probability distribution of luminescence dates reveals five maxima, and when represented as bars (date ± single standard deviation) it allows the identification of seven distinct groups of dates;
- probability distribution of ^{14}C dates exhibits six maxima for the range 50–15 cal kBP, and the bar representation (68.3% confidence intervals) distinguishes twenty groups of dates (overlapping for older ages);
- GS-2a/GI-1 transition is characterized by the rising slope of the PDF curve;
- within GI-1 two clear maxima can be observed: one correlated with the GI-1c2/GI-1c3 transition and the other correlated with the GI-1a/GS-1 transition;
- GS-1/Holocene transition is marked by a steep increase in the slope of the PDF curve.

The dataset for the Carpathian region comprises only 59 radiocarbon dating results. Analyzing their probability distributions alongside the INTIMATE stratigraphy reveals the following observations:

- probability distribution of ^{14}C dates for the range 15–50 cal kBP reveals two distinct narrow maxima correlated with GI-11 and GI-3, and four broader maxima. The bar representation of these dates (68.3% confidence intervals) distinguishes fourteen (overlapping) groups of dates;
- GI-1 warming is marked by an increase in the PDF curve;
- in the range of 11.7–15 cal kBP, three distribution maxima are evident: the first correlated with GI-1c2, the second with the GI-1a/GS-1 transition, and the third with the GS-1/Holocene transition.

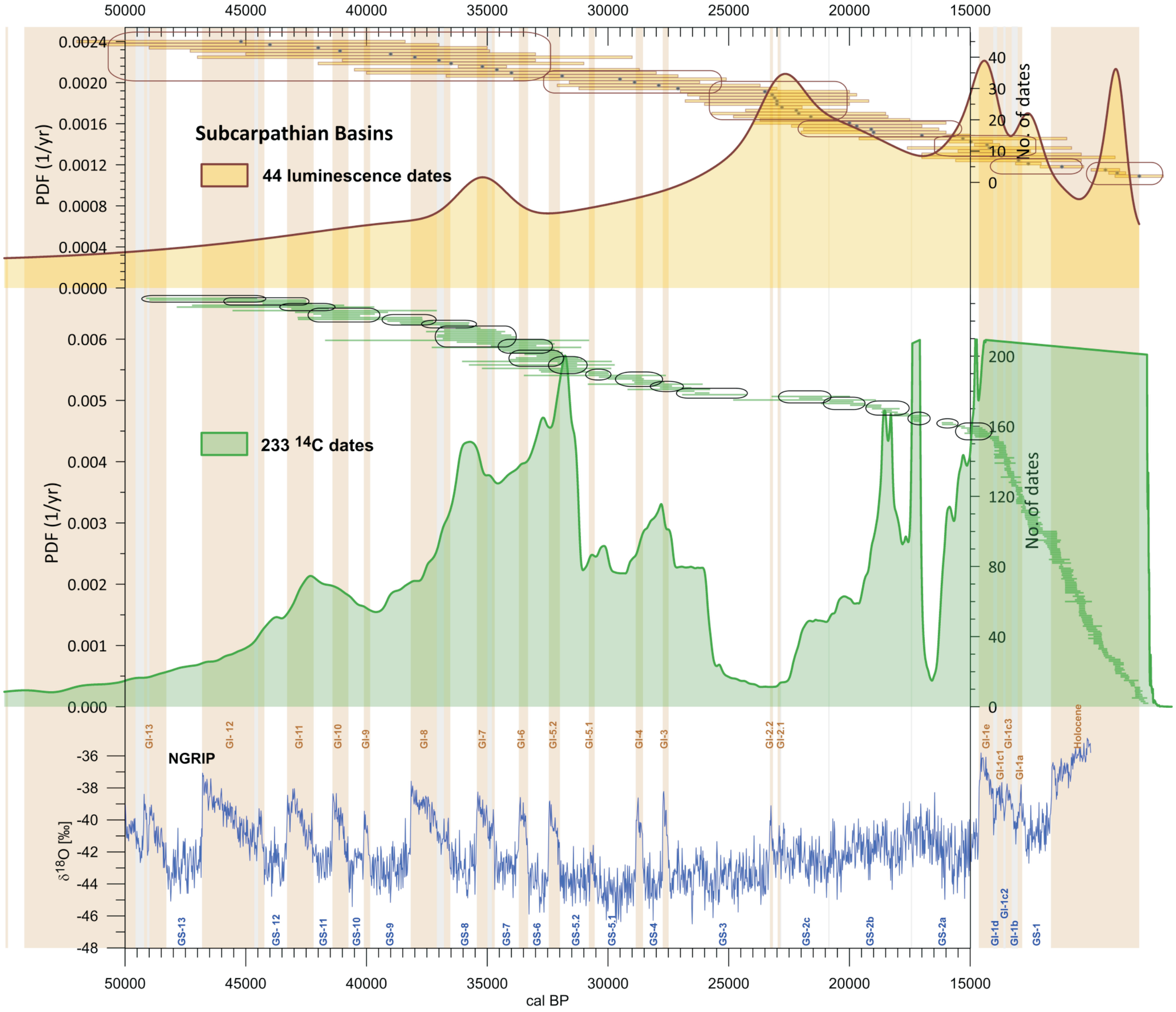

Fig. 5. Summed distributions of radiocarbon and luminescence dates for the Subcarpathian Basins region

Date clusters have been marked by rounded rectangles around the bars representing the 68.3% probability intervals of individual dates; PDF chart for the ^{14}C dates for the range <15 cal kBP has been truncated at the top for clarity

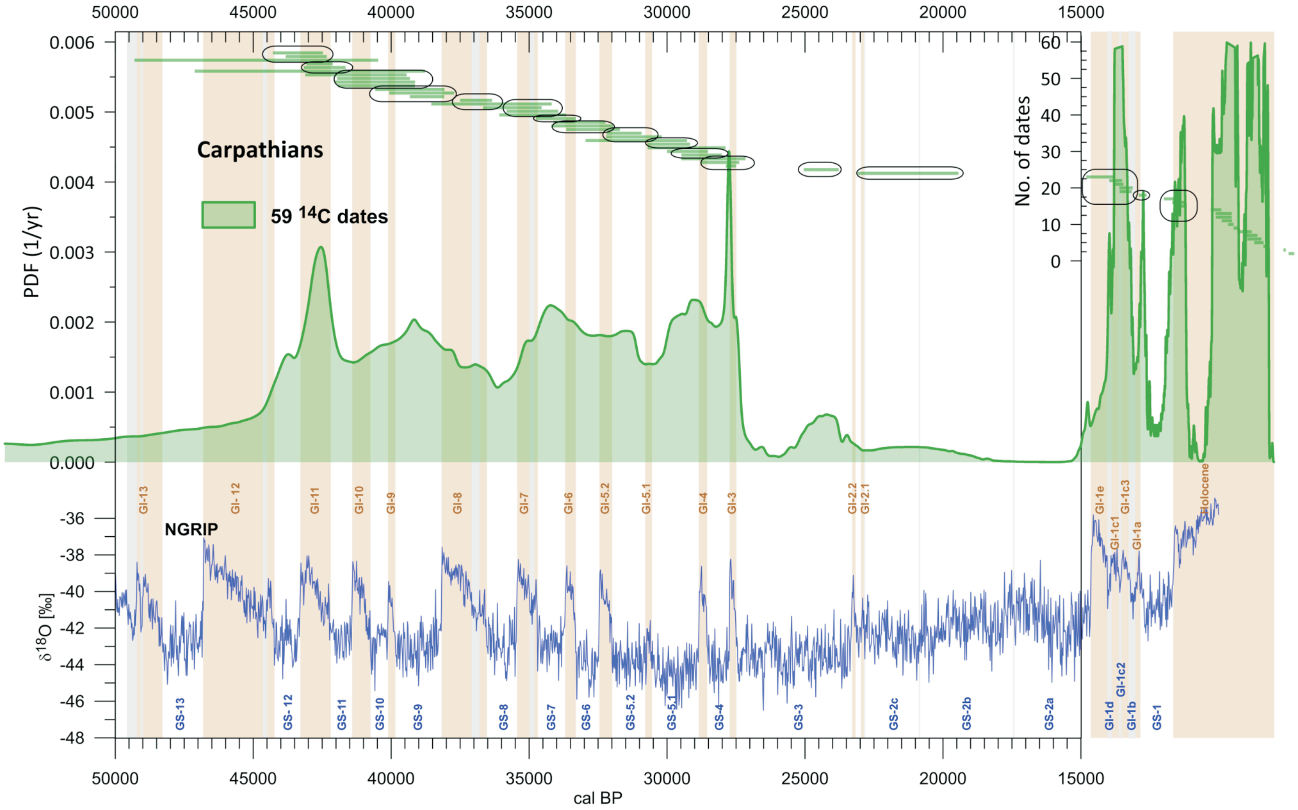

Fig. 6. Summed distributions of radiocarbon dates for the Carpathian region

Date clusters have been marked by rounded rectangles around the bars representing the 68.3% probability intervals of individual dates; PDF chart for the ^{14}C dates for the range <15 cal kBP has been truncated at the top for clarity

DISCUSSION

FACTS ABOUT THE REGIONS ANALYSED DERIVED FROM THE ANALYSIS OF INDIVIDUAL SITES

ŁÓDŹ REGION (ŁR)

The history of the development of river valleys in the ŁR dates back to the termination of the Saalian Glaciation, when erosion reshaped the landscape, transforming the depressions left by the glaciation into river valleys (e.g., Krzemiński, 1965; Turkowska, 1988, 2006; Wachecka-Kotkowska, 2004; Forysiak, 2005). During the Eemian interglacial, fluvial processes reached a stable equilibrium between erosion and accumulation. Aggradational processes predominated during the Early Vistulian (109–71 cal kBP) (Krzemiński, 1965; Turkowska, 1988; Petera, 2002).

In most river valleys, the transition from the Early Vistulian (109–71 cal kBP) to the Lower Plenivistulian (71–57 cal kBP) marked a period of erosion dominance, which might have extended into the Middle Plenivistulian (57–29 cal kBP) (Turkowska, 1988; Kamiński, 1993; Goździk and Zieliński, 1999; Kobojek, 2000; Wachecka-Kotkowska et al., 2014). Nevertheless, in the Warta Valley and some of its tributaries, sedimentary records suggest accumulation during the extended cooling of the Lower Plenivistulian, and the erosion phase occurred only at the end of this period (Krzemiński, 1965; Manikowska, 1996; Wachecka-Kotkowska et al., 2014).

A period of intense aggradation in the river valleys of the Łódź region begins in the Middle Plenivistulian (Krzemiński, 1965; Turkowska, 1988; Krzyszkowski, 1990; Kamiński, 1993; Manikowska, 1996; Petera, 2002; Wachecka-Kotkowska, 2004; Forysiak, 2005; Wachecka-Kotkowska et al., 2014). This increase in sediment deposition was accompanied by a significant contribution of material via lateral transport from the valley slopes (Turkowska, 1988; Kobojek, 2000; Wachecka-Kotkowska, 2004). Organic and mineral-organic sediments from this period were also deposited on the valley bottoms (Krzyszkowski, 1990; Kamiński, 1993; Manikowska, 1996; Petera, 2002). Aggradational trends continued into the Upper Plenivistulian (29-15 cal kBP), but the sedimentation style shifted towards coarser materials in the braided river sedimentary environment. This transition is marked by an unconformable contact between Middle and Upper Plenivistulian deposits (Turkowska, 1988; Krzyszkowski, 1990; Kamiński, 1993; Petera, 2002; Wachecka-Kotkowska, 2004; Forysiak, 2005; Wachecka-Kotkowska et al., 2014). Despite the severe climate and the dominance of higher-energy sedimentation styles, organic and mineral-organic sediments accumulated and were preserved under favourable conditions (e.g., Krzyszkowski, 1990; Petera, 2002).

During the transition from the Upper Plenivistulian (29–15 cal kBP) to the Late Vistulian (15–11.7 cal kBP), rivers gradually left their wide braided channels while the runoff was concentrated in narrower zones, which was accompanied by erosion. This erosional phase led to the morphological separation of the Plenivistulian high terrace. The trend towards stabilization of fluvial systems was interrupted by a sudden cooling at the Late Vistulian termination and accumulation again dominated. Many rivers have returned to braiding (Turkowska, 1988) or anabranching systems have developed (Petera-Zganiacz et al., 2015). The transition from the Pleistocene to the Holocene in the valleys of the Łódź region is marked by an erosional phase, contributing to the separation of the Late Vistulian low terrace (Krzemiński, 1965; Turkowska, 1988; Kobojek, 2000; Wachecka-Kotkowska, 2004, Forysiak, 2005).

HOLY CROSS MOUNTAINS (HCM)

The reorganisation of the network of small rivers in the HCM after the Saalian Glaciation began on the surface of glacigenic sedimentary cover, local periglacial cover and Paleogene and Neogene weathered deposits (Ludwikowska-Kędzia, 2018). This polygenetic cover of deposits of varying thickness only partially concealed the varied structural relief of the Paleozoic massif. The dissection of this cover, initiated by climatic changes in the Early Vistulian (MIS5d-a), occurred asynchronously in individual sections of the longitudinal profiles of the valleys in the HCM. The vertical and spatial extent of the erosion surface varied. It depended on the position of the valleys relative to the pattern and features of the structural relief of the HCM.

In the Middle Plenivistulian (MIS4) in the river valleys of the HCM, aggradational tendencies predominated (Lindner, 1984; Kowalski, 2002; Ludwikowska-Kędzia et al., 2006). The source of the fluvial sediments was not only the glacial deposit accumulations, but mainly local periglacial slope covers. These became accessible as a result of the widening of valley bottoms due to thermal erosion of braided river channels and/or activation of denudational processes (Lindner, 1984; Kowalski, 2002; Ludwikowska-Kędzia et al., 2006).

In the Middle Plenivistulian (MIS3), under conditions of short-term warm and cold climatic fluctuations favourable for the development of forest-tundra vegetation communities (Ludwikowska-Kędzia, 2000), the trend of aggradation continued in the HCM river valleys. Due to the activation of denudation processes on the slopes of ridges and valleys in this period, deluvia (mainly loess) and colluvia often contributed to an increase in the thickness of deposits that accumulated in the valley bottoms (Kowalski, 2002; Ludwikowska-Kędzia et al., 2006; Wachecka-Kotkowska and Ludwikowska-Kędzia, 2007). These processes also caused the areal expansion of the slope deposits towards the valley axis (Kowalski, 2002), which obscured the real amount of fluvial aggradation in the valleys (Ludwikowska-Kędzia, 2021). The Middle Plenivistulian polygenetic level of the valley bottom was formed (Wachecka-Kotkowska and Ludwikowska-Kędzia, 2007).

During the Upper Plenivistulian (MIS2), aggradation dominance occurred in the river valleys of the HCM under particularly harsh climatic conditions Ludwikowska-Kędzia, 2000; Krupa, 2013). Sediments in the valleys were strongly affected by aeolian processes, and there was an accumulation of rhythmically stratified deposits of aeolian-deluvial origin on the valley slopes (Ludwikowska-Kędzia et al., 2018).

Asynchronous dissection of the Middle and Upper Plenivistulian bottoms of the river valleys in the HCM took place as the Upper Plenivistulian gave way to the Late Vistulian (Ludwikowska-Kędzia, 2000; Kowalski, 2002; Krupa, 2013). In the valley bottoms there are preserved systems of erosion and accumulation as Plenivistulian terraces (with varying relative heights of 2–15 m) and/or their basements (mostly the lower part of the Middle Plenivistulian valley fill), which are erosional remnants hidden under the cover of younger (mainly Holocene) deposits. Some of the terraces most probably represent the toe-cut type of terraces (Ludwikowska-Kędzia, 2021), i.e. the truncated toes of tributary alluvial fans (after Larson et al., 2015).

The Late Vistulian was mainly a period of transformation of the river channel pattern in the HCM from braided to meandering (Ludwikowska-Kędzia, 2000; Kowalski, 2002), locally with the stage of development of large meanders (Krupa, 2013). Concentration of flow favoured dissection of valley bottoms, shortening of river channels, cutting of meanders and biogenic accumulation in oxbow lakes and valley mires (Szczepanek, 1961; Ludwikowska-Kędzia, 2000; Żurek et al., 2014). The erosional episodes were locally synchronous with the filling of the newly formed dissections (Ludwikowska-Kędzia, 2000). During the Younger Dryas cooling, braiding channels and aggradational tendencies were recorded in the river valley bottoms of the HCM. This short aggradational phase is represented by silts and sands with cryogenic deformation structures (Ludwikowska-Kędzia, 2018). At that time, dunes penetrated the river valleys, and the fluvial sediments were subject to strong aeolian processing (Jaśkowski, 1999; Okupny et al., 2019).

The transition from the Late Vistulian to the Holocene has been recorded in the river valleys of the HCM as an erosional phase that occurred asynchronously in individual sections of the valleys and was of varying intensity (Ludwikowska-Kędzia, 2000; Kowalski, 2002; Krupa, 2013). It resulted in the formation of a terrace covered by the Holocene alluvium.

CARPATHIANS AND SUBCARPATHIAN BASINS

During the Vistulian period in the river valleys of the Carpathians and Subcarpathian Basins, erosional and accumulative processes occurred, resulting in the formation of 2–3 terrace levels with heights of 15–20 m, 8–12 m, and 6–8 m above the levels of contemporary riverbeds (Starkel, 2001; Gębica, 2004).

During the Early Vistulian (MIS5d-a), wide erosional plains were formed, and rivers cut through the former alluvial covers (Starkel, 2014).

In the Lower Plenivistulian (MIS4) in the Carpathians and Subcarpathian Basins, significant aggradation occurred due to a marked deterioration in climatic conditions. The channel alluvia from this period are dated in the Vistula Valley east of Kraków using the TL method to near 70 ka (Gębica, 1995).

The Middle Plenivistulian period (MIS3) was characterized by an accumulation of alluvia, interspersed with phases of incision. In the Carpathians, aggradation progressed with the supply from slopes, recorded in the interweaving of river and slope covers (colluvial and solifluctional) (Starkel et al., 2017). Two to three interstadial sedimentary units, separated by erosional surfaces, seem well-documented. Erosion in the Vistula Valley and its Carpathian tributaries is dated to before 50 cal kBP. Around 48–36 kBP (over 40.9–50 cal kBP), the filling of oxbow lakes and shallow thermokarst depressions occurred. At the end of ~36 kBP (~41 cal kBP), incision of the alluvia took place, initiating the deposition of a separate alluvial cover, currently forming a terrace with a height of 15–20 metres.

A clear phase of river erosion occurred in the Upper Plenivistulian (MIS2) before the Last Glacial Maximum, around 20–25 kBP (~24–29 cal kBP), associated with progressing climate aridification resulting from a shift from oceanic to more continental conditions (Gębica et al., 2015). Probably, the frequency of floods also decreased during this time, leading to channel deepening and/or widening, reducing the vertical extent of flood inundations. During this period, the deposition of a separate cover was initiated, currently forming a terrace with a height of 8–12 m. On the higher terrace, at 15–20 m, accumulation of loess and sand occurred due to channel deepening and/or reduced flood extent. The lower terrace, at 8–12 m, with deposits from the Middle Plenivistulian, was cut by the alluvia of the braided river, whose age predates the Late Vistulian. The deposits of this terrace are dated using the luminescence method to 17–24 kBP, placing them in the Upper Plenivistulian (MIS2) (Starkel, 1995; Mamakowa et al., 1997; Gębica, 2004). This terrace at the top was covered by dunes.

At the end of the Upper Plenivistulian (13–15 kBP, 15.3–18.6 cal kBP), riverbeds deepened, accompanied by changes in channel development from braided to meandering. The age of the oldest meandering channels, dated by the conventional radiocarbon method to the end of the Plenivistulian in the San Valley near Stubno in the light of the AMS dating, turned out to be significantly younger (Klimek et al., 1997; Gębica et al., 2022). Most dated infills of large palaeomeanders come from the Allerød and Younger Dryas (Szumański, 1983; Starkel, 1995, 2003; Klimek, 1995; Gębica et al., 2022). In the Vistula Valley below Kraków there was even a return to a braided riverbed (Kalicki, 1991). Presumably, many river channels had a transitional (meandering-braided) character during this time (Starkel, 2001).

GENERAL REMARKS BASED ON PRESENT RESEARCH

The possibilities of reconstructing the fluvial environmental responses to climate changes based on data from individual sites are limited due to their sporadic nature. However, collective analysis of ^{14}C dates has revealed that nearly every transition between Greenland Stadials (GS) and Greenland Interstadials (GI) has been recorded in fluvial environments. Regional differences in these responses have, though, been observed.

Detailed reconstructions are most achievable with precise dates, such as AMS radiocarbon dates, which are highly desirable for this type of analysis. However, our research indicates that age determinations made prior to the AMS technique's advent can also be valuable. The comprehensive analysis of data from various non-continuous profiles consistently reveals a correlation between fluvial events and climate changes recorded in Greenland ice cores. It is important to note that this collective analysis, in its presented form, does not distinguish whether the environmental changes reflected in the PDF distribution peaks are related to sediment accumulation or erosion. For such a distinction, more detailed data from individual sites are required. The analysis we provide informs us solely about the occurrence of changes in the fluvial environment.

In the type of analysis described, the fact of preferential sampling for dating is very helpful. This fact simultaneously determines the great usefulness of even individual age determinations. Therefore, not only the number of dates but also their quality has important interpretative value. For all sites analysed, dating samples were taken near places where there was a change in the type of sediment. Thanks to this, for example, the date of the bottom of the organic filling of the palaeochannel will inform us that it must have been abandoned earlier. In turn, the date of the top of the organic fill covered with mineral deposits will inform us about the event that occurred after it. However, a thin intercalation of organic material in the mineral deposits will be able to give us a date coeval in age with the fluvial event.

Another important aspect to consider is that a high peak does not always indicate a large accumulation of dates; it can result from a single precise date. Therefore, it is crucial to pay attention to the number of dates contributing to a particular peak, expressed as the number of bars representing the 68.3% confidence intervals for individual dates.

Closely situated regions, namely the Subcarpathian Basins and the Carpathians, present a different pattern in terms of radiocarbon date PDF curves (cf. Figs. 4 and 5). In the Carpathians, there is a distinct gap in the number of dates evident in the PDF curve between 15 and 27 cal kBP (where we have only two dates), whereas in the Subcarpathian Basins, this gap is much smaller, occurring mainly between 22 and 25.5 cal kBP. The most plausible explanation is the influence of local conditions (associated with colder climates in mountainous areas), but this factor is also compounded by the smaller number of dates available in the dataset for the Carpathians.

While radiocarbon dates yield the most detailed results, even in the case of luminescence dates, collective analysis can provide valuable insights. This is particularly applicable to the HCM, where dating results are primarily obtained using the TL (thermoluminescence) or OSL (optically stimulated luminescence) methods.

Date clusters are visible on the PDF curve as 5 distinct peaks. The number of dates constituting a given phase can be read by comparing sectional charts representing single dates at $\pm 1\sigma$ (upper part of the Fig. 7). Although uncertainties of the luminescence dates are large and the distributions of these dates overlap, the upper part of the graph, where the medians are marked, allows us to attempt to isolate subphases from a to d - see rounded rectangles at the top of the Figure 4. The compilation of luminescence dates for the fluvial environment of the HCM and their grouping into "event series" (E) allowed for the identification of three main phases of fluvial process activation (see Fig. 7). The oldest phase, FPI-1, and the youngest, FPI-3, show a relationship with the end of prolonged, cold stadial conditions of MIS4 and MIS2, respectively. By contrast, phase FPI-2 correlates well with a period of rapid and frequent climate changes (but with increasingly colder cold episodes), preceded by relatively long-lasting interstadial conditions of MIS3. The duration of the activation phases identified (from the oldest to the youngest) decreases, which may be associated with the reduction of the uncertainty values of luminescence dates of increasingly younger deposits. In phase FPI-2, during the middle part of MIS3 (42–36 kBP), a change in the type of sediments that accumulated in the fluvial environment HCM is recorded, from sandy to silty.

Small rivers in the HCM react quickly throughout their longitudinal profile to changes in climatic conditions. The record of this reaction in the bottoms of their valleys, although more dynamic, is less durable compared to the valleys of large rivers. Hence, for small rivers in the HCM, local conditions (geological structure and relief) become significant. These, in turn, determine the scale of climatic changes that will be recorded in the valleys. The FPI phases and F events identified in the fluvial environment activity in HCM mainly record evidence of cold, stadial climatic conditions in the Plenivistulian, mainly long-lasting, occasionally brief. The weak registration of interstadial conditions in the river valley deposits of the HCM until the middle of MIS3 is most likely related to the lack of favourable lithological conditions in the valley bottoms for the formation and preservation of biogenic sediments.

For a fuller interpretation of the grouping of luminescence dates, that is, the identified events and phases of the functioning of the fluvial environment in the HCM, it becomes important to consider the "lithological background". A good illustration of this thesis is the change in the type of sediments accumulated in the fluvial environment of HCM between the FPI-1 and FPI-2 phases (MIS3), i.e. the appearance of silty deposits. Their share is clearly visible in the bipartite structure of the valley bot-

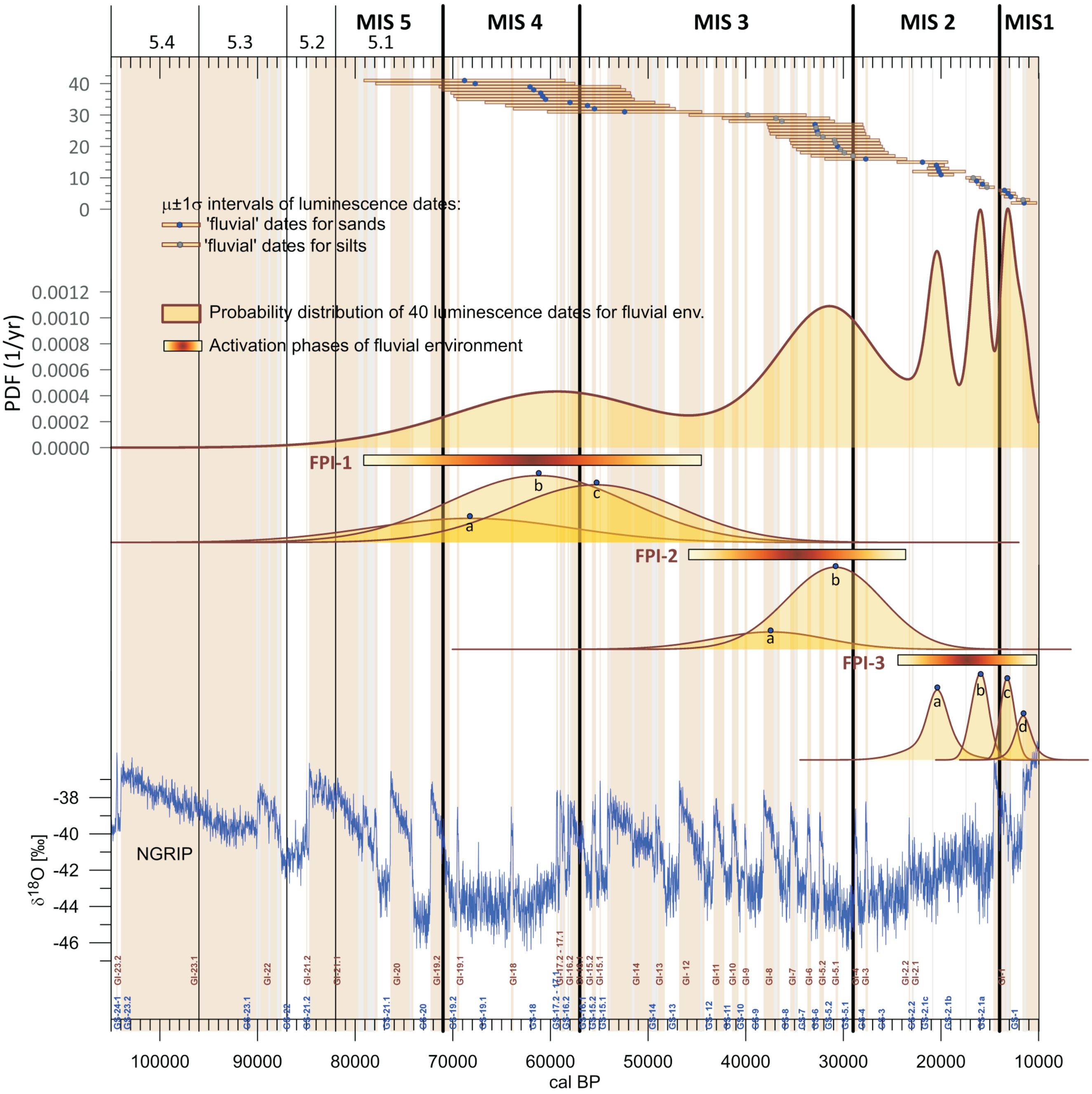

Fig. 7. Identification of fluvial events (marked with the letters a–d) and activity phases (marked as bars with gradient fill) for the HCM region

A phase (determined based on the set of TL, OSL dates) includes several fluvial events, with the time range of a single fluvial event corresponding to a 68.3% confidence interval; phase indicates in which part of the oxygen curve from the NGRIP core and INTIMATE stratigraphy these fluvial events occurred, allowing them to be correlated with palaeoclimatic conditions

tom from this period (Ludwikowska-Kędzia, 2000; Wachecka-Kotkowska and Ludwikowska-Kędzia, 2007). The lower part consists of thick, extra-channel silts and silty sands, and the upper part of in-channel sands transformed by aeolian processes. The change in grain size and type of alluvium accumulated in the FPI-2 phase compared to the Plenivistulian phase is a record of intense denudation of the younger lower loess cover in the region (Jersak et al., 1992). It led to the formation of silts of different generations in the bottoms of the Holy Cross river valleys, which, as impermeable layers resistant to erosion, determined the development and preservation of organic and mineral-organic sediments in the HCM (Ludwikowska-Kędzia, 2000, 2018). Reducing the uncertainty of luminescence dates for increasingly younger deposits results in shortening the duration of the identified phases of activation of fluvial processes FPI in the HCM.

Similar distinctions of events of increased fluvial activity have also been conducted for the ŁR and the Subcarpathian Basins. Figure 8 shows a comparison of events for all these regions.

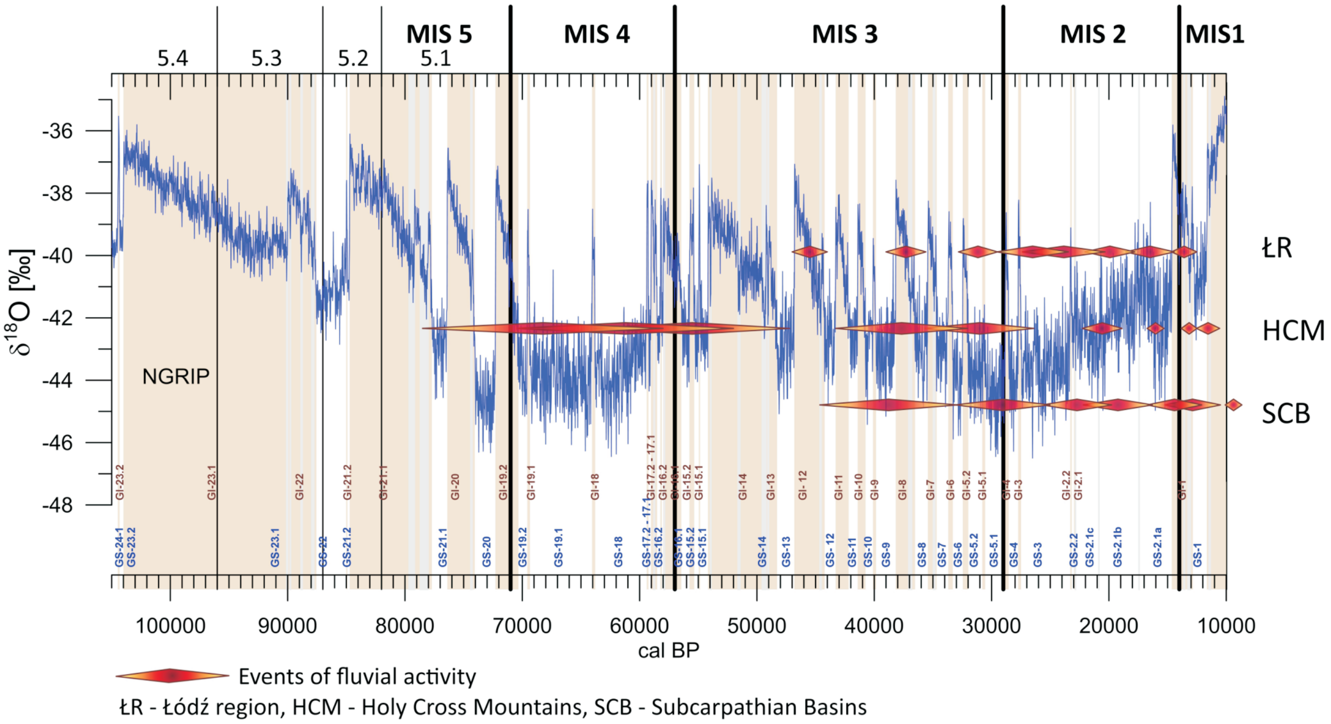

Fig. 8. Comparison of events of increased fluvial activity recorded in the accumulation of luminescence dates for the Łódź region, Holy Cross Mountains and Subcarpathian Basins

The temporal range of a single fluvial event corresponds to a 68.3% confidence interval

In the HCM, phases of fluvial environment activation are associated with stadial periods and the transitional period from long-lasting cold (stadial) conditions to interstadial (e.g., MIS4 and MIS2) and/or with short-term, alternating stadial and interstadial periods, with a cooling trend (MIS3). In the Subcarpathian Basins, the event pattern is similar to that of the HCM, although events in the Subcarpathian Basins valleys seem to correlate with the coldest stadial conditions of MIS3 and MIS2. In the ŁR, an evident series of events associated with the cold conditions of MIS2 is clearly discernible. And, data from ŁR from the Warta River Valley indicate that increased fluvial activity also occurred during MIS4.

The results described show a very good correlation of PDF curves and date accumulations with the oxygen curve and INTIMATE stratigraphy. Some discrepancies between the climatic signal recorded in the PDF and the oxygen curve from the NGRIP core can be attributed to several factors:

- time required for the environment to respond to climate change, which depends on the geographic location of the sites, including morphological features (mountains, foothills, highlands, or lowlands) and their position in the river's longitudinal profile;
- influence of local conditions, such as widening or narrowing of river sections;
- variations in the sizes of the rivers analysed, leading to different rates of response to climatic changes and varying degrees of preservation of their records in the sedimentary succession and in valley relief;
- fact that, in most cases, samples were dated from locations within the sedimentary profile before or after a visible change in the sedimentological record, rather than precisely at the layer boundary;
- statistical uncertainties of dates, which increase as the age of deposits increases. Consequently, peaks become lower and wider in increasingly older sedimentary units.

CONCLUSIONS

The analyses performed allowed for the merging of scattered information from individual sites and their comparison against the background of the INTIMATE stratigraphy. The study has demonstrated the value of analysing summed Probability Density Functions (PDFs) of radiocarbon and luminescence dates for collective geochronological analysis. It has also highlighted that discontinuous records of fluvial environmental responses in such analyses provide more detailed insights than studies conducted for individual sites. A strong correlation was observed between the peaks of radiocarbon date PDF curves and GS/GI or GI/GS transitions, with greater precision in reconstructions for more recent time frames. Each of these transitions since GS-13/GI-13 is reflected in accumulations of ^{14}C dates. By contrast, accumulations of luminescence dates are primarily associated with stadial periods.

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REFERENCES

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon, 51: 337–360. https://doi:10.1017/s0033822200033865

Bronk Ramsey, C., 2017. Methods for summarizing radiocarbon datasets. Radiocarbon, **59**: 1809–1833. https://doi:10.1017/RDC.2017.108

Dzieduszyńska, D., 2017. Usefulness of a set of radiocarbon dates for the reconstruction of changes in the environment of the Vistulian decline in Central Poland (in Polish with English summary). Acta Geographica Lodziensia, **106**: 117–127. https://doi:10.26485/agl/2017/106/9

Dzieduszyńska, D.A., 2019. Timing of environmental changes of the Weichselian decline (18.0–11.5 ka cal BP) using frequency distribution of ^{14}C dates for the Łódź region, Central Poland. Quaternary International, **501**: 135–146. https://doi.org/10.1016/j.quaint.2017.08.012

Dzieduszyńska, D.A., Michczyńska, D.J., Petera-Zganiacz, J., Wachecka-Kotkowska, L., Wieczorek, D., Krzyszkowski, D., 2023. Impacts of large-scale climate oscillations on fluvial sediments in Central Poland: evidence from geochronological analysis. Geochronometria, **50**: 224–249. https://doi:10.2478/geochr-2023-0018

Forysiak, J., 2005. Development of the Warta River valley between Burzenin and Dobrów after the Warta stage (in Polish with English summary). Acta Geographica Lodziensia, **90**: 1–116.

Gębica, P., 1995. Evolution of Vistula River valley between Nowe Brzesko and Opatowiec in the Vistulian and Holocene (in Polish with English summary). Dokumentacja Geograficzna, **2**: 1–191.

Gębica, P., 2004. The course of fluvial accumulation during the upper Vistulian in Sandomierz Basin (in Polish with English summary). Prace Geograficzne, **193**: 1–229.

Gębica, P., Michczyńska, D.J., Starkel, L., 2015. Fluvial history of the Sub-Carpathian Basins (Poland) during the last cold stage (60–8 cal ka BP). Quaternary International, **388**: 119–141. https://doi:10.1016/j.quaint.2015.06.012

Gębica, P., Michno, A., Sobucki, M., Wacnik, A., Superson, S., 2022. Chronology and dynamics of fluvial style changes in the Younger Dryas and Early Holocene in Central Europe (lower San River, SE Poland). Science of the Total Environment, **830**, 154700. Elsevier. https://doi:10.1016/j.scitotenv.2022.154700

Goździk, J.S., Zieliński, T., 1999. Plenivistulian and Late Vistulian sediments of the Struga Żłobnicka series – a characteristic example of valley infill in central Poland. Łódź Periglacial Symposium "Periglacial Environments: Past, Present and Future", Łódź, 27–30 September 1999, University of Łódź, IIIrd Excursion Book: 82–84.

Jaśkowski, B., 1999. Interrelationship of Late Vistulian dune-forming processes and neotectonics activity of a basement complex in the Holy Cross Mts. region (in Polish with English summary). Przegląd Geologiczny, **47**: 1032–1036.

Jersak, J., Sendobry, K., Śnieszko, Z., 1992. Postwarciańska ewolucja wyżyn lessowych w Polsce (in Polish). Prace Naukowe Uniwersytetu Śląskiego, **1227**.

Kalicki, T., 1991. The evolution of the Vistula River valley between Cracow and Niepołomice in Late Vistulian and Holocene times. In: Evolution of the Vistula River Valley During the last 15 000 Years. Part IV (ed. L. Starkel): 11–37. Ossolineum, The Publishing House of the PAS, Wrocław. https://rcin.org.pl/dlibra/publication/35208/edition/18826

Kamiński, J., 1993. Late Vistulian and Holocene transformation of the Moszczenica River valley as a result of changes of the natural environment and man activity (in Polish with English summary). Acta Geographica Lodziensia, **64**: 1–104.

Klimek, K., 1995. The role of drainage basin orography in the river channel pattern transformation during Late Vistulian, Subcarpathian Oswiecim Basin, Poland. Quaestiones Geographicae, **4** (Special Issue): 147–153.

Klimek, K., Łanczont, M., Bałaga, K., 1997. Późnovistuliańskie i holoceńskie wypełnienie paleomeandra w dolinie Sanu koło Stubna (in Polish). In: Glacjał i peryglacjał Kotliny Sandomierskiej i przedgórza Karpat w okolicy Przemyśla, Krasiczyn 22–24 IX 1997 (ed. M. Łanczont): 60–71 Wyd. Instytutu Nauk o Ziemi UMCS, Lublin.

Kobojek, E., 2000. Morphogenesis of the Rawka valley (in Polish with English summary). Acta Geographica Lodziensia, **77**: 1–157.

Kowalski, B.J., 2002. Geneza i wiek osadów terasy zalewowej i nadzalewowej (wysokiej) środkowego odcinka doliny Lubrzanki w Górach Świętokrzyskich (in Polish). Prace Instytutu Geografii Akademii Świętokrzyskiej w Kielcach, **8**: 151–215.

Krupa, J., 2013. Natural and anthropogenic factors influenced Czarna Nida river valley during the Late Glacial and Holocene (in Polish with English summary). Folia Quaternaria, **81**: 5–174.

Krzemiński, T., 1965. Przełom doliny Warty przez Wyżynę Wieluńską (in Polish). Acta Geographica Lodziensia, **21**: 1–95.

Krzyszkowski, D., 1990. Middle and Late Weichselian stratigraphy and palaeoenvironments in central Poland. Boreas, **19**: 333–350. https://doi:10.1111/j.1502-3885.1990.tb00138.x

Larson, P.H., Dorn, R.I., Faulkner, D.J., Friend, D.A., 2015. Toe-cut terraces: a review and proposed criteria to differentiate from traditional fluvial terraces. Progress in Physical Geography, **39**: 417-439. https://doi.org/10.1177/0309133315582045

Lindner, L., 1984. Region świętokrzyski (in Polish). In: Budowa Geologiczna Polski, t. 1, Stratygrafia, cz. 3b. Kenozoik – czwartorzęd (ed. J.E. Mojski): 33–35, 65–73. Wyd. Geol., Warszawa.

Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic δ^{18}O records. Paleoceanography, **20**: 1–17. https://doi:10.1029/2004PA001071.

Lorraine Lisiecki's Home Page https://www.lorraine-lisiecki.com/stack.html. Accessed January 8, 2024.

Ludwikowska-Kędzia, M., 2000. Ewolucja środkowego odcinka doliny rzeki Belnianki w późnym glacjale i holocenie (in Polish). Wydawnictwo Akademickie Dialog, Warszawa.

Ludwikowska-Kędzia, M., 2018. Litologia, geneza i stratygrafia osadów czwartorzędowych w południowej części Gór Świętokrzyskich (in Polish). Uniwersytet Jana Kochanowskiego w Kielcach. Instytut Geografii, Kielce.

Ludwikowska-Kędzia, M., 2021. "Middle Polish fluvial high terrace" in the river valleys of the Kielce-Łagów Depression (Holy Cross Mountains, Poland) – fact or myth? Studia Geomorphologica Carpatho-Balcanica, **55**: 129–152.

Ludwikowska-Kędzia, M., Wiatrak, M., Olszak, I., Bluszcz, A., 2006. Lithostratigraphy of the Pleistocene high meadow terrace of the Łagowica Valley near Masłowiec (SE part of the Holy Cross Mountains) (in Polish with English summary). Przegląd Geologiczny, **54**: 953–962.

Ludwikowska-Kędzia, M., Adamiec, G., Skurzyński, J., Jary, Z., 2018. Pochodzenie i wiek osadów budujących terasę wyższą przełomowego odcinka doliny rzeki Lubrzanki w Górach Świętokrzyskich (in Polish). Plejstocen Gór Świętokrzyskich. XXV Konferencja Stratygrafia Plejstocenu Polski; Kielce (ed. M. Ludwikowska-Kędzia and M. Wiatrak): 138–139.

Mamakowa, K., Starkel, L., Boratyn, J., Brud, S., 1997. Stratigraphy of the Vistulian alluvial fills in the Wisłoka valley north of Dębica. Studia Geomorphologica Carpatho-Balcanica, **31**: 83–99.

Manikowska, B., 1996. Bicyclicity in the evolution of the periglacial environment in Central Poland during the Vistulian (in Polish with English summary). Biuletyn Państwowego Instytutu Geologicznego, **373**: 97–106.

Marks, L., 2002. Last Glacial Maximum in Poland. Quaternary Science Reviews, **21**: 103110. https://doi.org/10.1016/S0277-3791(01)00086-5.

Marks, L., 2023. Quaternary stratigraphy of Poland – current status. Acta Geologica Polonica, **73**: 307–340. https://doi:10.24425/agp.2023.145614

Marks, L., Dzierżek, J., Janiszewski, R., Kaczorowski, J., Lindner, L., Majecka, A., Makos, M., Szymanek, M., Tołoczko-Pasek, A., Woronko, B., 2016a. Quaternary stratigraphy and palaeogeography of Poland. Acta Geologica Polonica, **66**: 403–427. https://doi:10.1515/agp-2016-0018

Marks, L., Gałązka, D., Woronko, B., 2016b. Climate, environment and stratigraphy of the last Pleistocene glacial stage in Poland. Quaternary International, **420**: 259–271. https://doi:10.1016/j.quaint.2015.07.047

Marks, L., Bitnias, A., Błaszkiewicz, M., Börner, A., Guobyte, R., Rinterknecht, V., Tylmann, K., 2022a. Chapter 49 – Northern Central Europe: glacial landforms from the Last Glacial Maximum. In: European Glacial Landscapes. Maximum Extent of Glaciations (eds. D. Palacios, P.D. Hughes, J.M. García-Ruiz and N. Andrés): 381–388. https://doi.org/10.1016/B978-0-12-823498-3.00054-6

Marks L., Grabowski J., Stępień U. eds., 2022b. Mapa Geologiczna Polski w skali 1:500 000 (in Polish). Państwowy Instytut Geologiczny – Państwowy Instytut Badawczy, Warszawa.

Michczyńska, D.J., Hajdas, I., 2010. Frequency distribution of ^{14}C ages for chronostratigraphic reconstructions: Alaska region study case. Radiocarbon, **52**: 1041–1055. https://doi.org/10.1017/S0033822200046129.

Michczyńska, D.J., Pazdur, A., 2004. Shape analysis of cumulative probability density function of radiocarbon dates set in the study of climate change in the Late Glacial and Holocene. Radiocarbon, **46**: 733–744. https://doi:10.1017/S0033822200035773

Michczyńska, D.J., Michczyński, A., Pazdur, A., 2007. Frequency distribution of radiocarbon dates as a tool for reconstructing environmental changes. Radiocarbon, **49**: 799–806. https://doi.org/10.1017/S0033822200042673.

Michczyńska, D.J., Dzieduszyńska, D.A., Petera-Zganiacz, J., Wachecka-Kotkowska, L., Krzyszkowski, D., Wieczorek, D., Ludwikowska-Kędzia, M., Gębica, P., Starkel, L., 2022. Climatic oscillations during MIS 3-2 recorded in sets of ^{14}C and OSL dates – a study based on data from Poland. Radiocarbon, **64**: 1373–1386. https://doi:10.1017/RDC.2022.69

Michczyńska, D.J., Dzieduszyńska, D.A., Gębica, P., Krzyszkowski, D., Ludwikowska-Kędzia, M., Petera-Zganiacz, J., Wachecka-Kotkowska, L., Wieczorek, D., 2023. Analysis of summed probability density functions (PDFs) of radiocarbon and luminescence dates from discontinuous profiles of river deposits against the background of climate changes recorded in the NGRIP core (in Polish with English summary). Przegląd Geologiczny, **71**: 527–529. https://doi:10.7306/2023.41

Mojski, J.E., 2005. Ziemie polskie w czwartorzędzie. Zarys morfogenezy (in Polish). Państwowy Instytut Geologiczny, Warszawa.

Mol, J., 1997. Fluvial response to Weichselian climate changes in the Niederlausitz (Germany). Journal of Quaternary Science, **12**: 43–60. https://doi.org/10.1002/(SICI)1099-1417(199701/02)12:1<43::AID-JQS291>3.0.CO;2-0

Mol, J., Vandenberghe, J., Kasse, C., 2000. River response to variations of periglacial climate in mid-latitude Europe. Geomorphology, **33**: 131–148. https://doi.org/10.1016/S0169-555X(99)00126-9

Okupny, D., Malkiewicz, M., Pawłowski, D., Ludwikowska-Kędzia, M., Borówka, R.K., Forysiak, J., Michczyński, A., Jucha, W., Cybul, P., Żurek, S., 2019. Late Glacial palaeoenvironmental changes in the southern part of the Holy Cross Mountains based on the "Białe Ługi" peatland record. Studia Quaternaria, **36**: 119–135. https://doi:10.24425/sq.2019.126384

Petera, J., 2002. Vistulian valley deposits in the Uniejów Basin and their palaeogeographical significance (in Polish with English summary). Acta Geographica Lodziensia, **83**: 8–164.

Petera-Zganiacz, J., Dzieduszyńska, D.A., Twardy, J., Pawłowski, D., Płóciennik, M., Lutyńska, M., Kittel, P., 2015. Younger Dryas flood events: a case study from the middle Warta River valley (Central Poland). Quaternary International, **386**: 55–69. https://doi.org/10.1016/j.quaint.2014.09.074

Railsback, L.B., Gibbard, P.L., Head, M.J., Voarintsoa, N.R.G., Toucanne, S., 2015. An optimized scheme of lettered marine isotope substages for the last 1.0 million years, and the climatostratigraphic nature of isotope stages and substages. Quaternary Science Reviews, **111**: 94–106. https://doi:10.1016/J.QUASCIREV.2015.01.012

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. Quaternary Science Reviews, **106**: 14–28. https://doi:10.1016/j.quascirev.2014.09.007

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 (055 cal kBP). Radiocarbon, **62**: 725–757. https://doi:10.1017/RDC.2020.41

Starkel, L., 1995. New data on the Late Vistulian and Holocene evolution of the Wisłoka river valley near Dębica. Prace Geograficzne, Special Issue, **8**.

Starkel, L., 2001. Historia doliny Wisły: od ostatniego zlodowacenia do dziś (in Polish). Instytut Geografii i Przestrzennego Zagospodarowania PAN. Monografie, **2**: 1–263.

Starkel, L., 2003. Younger Dryas–Preboreal transition documented in the fluvial environment of Polish rivers. Global and Planetary Change, **35**: 157–167. https://doi:10.1016/S0921-8181(02)00133-9

Starkel, L., 2014. On some regularities in the evolution of relief of mountains and their forelands (exemplified by mountains of Eurasia) (in Polish with English summary). Wydawnictwo Akademickie SEDNO, Warszawa.

Starkel, L., Michczyńska, D.J., Gębica, P., 2017. Reflection of climatic changes during interpleniglacial in the geoecosystems of South-Eastern Poland. Geochronometria, **44**: 202–215. https://doi:10.1515/geochr-2015-0060

Starkel, L., Soja, R., Michczyńska, D.J., 2006. Past hydrological events reflected in Holocene history of Polish rivers. Catena, **66**: 24–33. https://doi:10.1016/j.catena.2005.07.008

Szczepanek, K., 1961. The history of the Late Glacial and Holocene vegetation of the Holy Cross Mountains (in Polish with English summary). Acta Palaeobotanica, **2**: 1–44. http://bomax.botany.pl/cgi-bin/pubs/data/article_pdf?id=2752

Szumański, A., 1983. Paleochannels of large meanders in the river valleys of the Polish Lowland. Quaternary Studies in Poland, **4**: 207–216.

Turkowska, K., 1988. Évolution des vallées fluviatiles sur le Plateau de Łódź au cours du Quaternaire tardif (in Polish with French summary). Acta Geographica Lodziensia, **57**: 1–157.

Turkowska, K., 2006. Geomorfologia regionu łódzkiego (in Polish). Wydawnictwo Uniwersytetu Łódzkiego, Łódź.

van Huissteden, J., Gibbard, P.L., Briant, R.M., 2001. Periglacial fluvial systems in northwest Europe during marine istope stages 4 and 3. Quaternary International, **79**: 75–88. https://doi.org/10.1016/S1040-6182(00)00124-5

Wachecka-Kotkowska, L., 2004. Evolution of the Luciąża River valley – local and climatic conditions (in Polish with English summary). Acta Geographica Lodziensia, **86**: 1–161.

Wachecka-Kotkowska, L., Ludwikowska-Kędzia, M., 2007. Plenivistulian level in the Luciąża (Piotrków Trybunalski Plateau/Radomsko Hills) and Belnianka (Holy Cross Mountains) river valleys comparison of structural and textural deposit features (in Polish with English summary). Acta Geographica Lodziensia, **93**: 107–132.

Wachecka-Kotkowska, L., Krzyszkowski, D., Klaczak, K., Król, E., 2014. Middle Weichselian pleniglacial sedimentation in the Krasówka river palaeovalley, Central Poland. Annales Societatis Geologorum Poloniae, **84**: 323–340.

Żurek, S., Kloss, M., Malkiewicz, M., 2014. Rezerwat Białe Ługi – geneza, budowa, wiek, walory przyrodnicze (in Polish). In: Monografia Cisowsko-Orłowskiego Parku Krajobrazowego (ed. A. Świercz): 261–376. Wydawnictwo UJK, Kielce.