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Colluvial deposits in loess gullies of southwestern Poland as an indicator of palaeoenvironmental changes and human impact

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Assessing the interactions between natural environmental change and land degradation due to human impact is crucial for palaeoenvironmental analysis in loess areas. However, the reconstruction of relief evolution in loess regions of SW Poland in relation to human impact of the first agrarian cultures, is not well understood by comparison with other loess areas in Poland. Therefore, our study aims to reconstruct land-use changes based on a palaeosol-bearing sedimentary sequence in a loess gully in this region. The research was conducted in the hilly region of SW Poland, where loess patches occur. To investigate prehistoric human impact in this area, we analysed dry valley systems near the village of Nowolesie, employing a combination of lithostratigraphic analysis and dating (radiocarbon and OSL) techniques. Within a 4.0 m-thick sedimentary succession filling the bottom of the gully, we identified loess-palaeosol sequences that represent a record of environmental changes during the Holocene. Our findings suggests that deforestation and dry valley transformation occurred during the Neolithic/early Bronze Age transition. Subsequently, erosional processes intensified during the Middle Ages. During this period, sediment dating to the Neolithic/Bronze Age was deposited in the upper parts of the gully and was later transported to the lower part of the main gully and redeposited in several episodes.

Key words: gully erosion, OSL dating, loess.

INTRODUCTION

Loess covers, due to the fertile soils developed on them, have been anthropogenically transformed since the Neolithic period in Europe and other parts of the world (Brown,1997; Lang, 2003; Lang and Bork, 2006; Leopold and Völkel, 2007; James, 2013; Schaetzl et al. 2018). A distinctive feature of the loess landscape is the occurrence of gullies, which research suggests are primarily impacted by land use change rather than climate change (Valentin et al., 2005; Ionita et al., 2015). Moreover, some studies suggest that not only deforestation but also a combination land overuse and periods with a high frequency of extreme rainfall events play a role in gully erosion. A combination of human-induced land use change and extreme rainfall events was also suggested by Lang and Mauz (2006).

The removal of the forest cover by humans leads to rapid rainwater runoff and intense soil erosion, resulting in gully development (Starkel, 1991; Śnieszko, 1995; Poesen et al., 2003; Valentin et al., 2005; Poręba et al., 2019). The eroded sediment accumulates on the bottoms of these gullies, forming colluvial deposits that are strongly linked to human activities such as settlement, clearing, mining, and agriculture (Leopold, 2003). The modern relief of loess areas is characterized by numerous gullies, many of which were likely initiated during the period of the first agricultural cultures.

Sedimentary deposits in valleys bottoms, gullies, alluvial fans, river terraces, closed depressions and sinkholes contain a record of temporal and spatial transformations in the landscape due to both land use by humans and to local climate changes. Analysis of these geoarchives provides valuable insight into past environmental conditions (Zygmunt, 2009; Dreibrodt et al., 2010; Fuchs et al., 2011; Zgłobicki and Zgłobicka, 2011; Dotterweich et al., 2012; Wistuba et al., 2018; Meyer-Heintze et al., 2020).

Soil erosion, especially gully erosion, is a major problem affecting agricultural productivity and environmental conditions in regions such as the European Loess Belt, the Chinese Loess Plateau and North America (Casali et al., 2000, 2006; Valentin et al., 2005; Kertészand and Gergely, 2011; Lehmkuhlet al., 2016; Li et al., 2017; Steinhoff-Knoppand and Burkhard, 2018; Frankl et al, 2018). Interdisciplinary research has established

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correlations between changes in the chemical composition, stratigraphy, and lithology of the loess deposits and archaeological records of historic land-use changes. These studies have traced the impact of such changes on hillslope erosion and sediment redistribution from the Neolithic, Bronze and Iron Ages, through the Middle Ages and the Industrial Revolution, and up to the present day (Poręba and Murray, 2006; Smolska, 2007; Zgłobicki and Rodzik, 2007; Szwarczewski, 2009).

However, little such research has been conducted in the Lower Silesia region of Poland, where an archaeological focus has dominated (Kulczycka-Leciejewiczowa, 1993; Ryzner and Owczarek, 2020).

The relationship between the economies of prehistoric settlements in loess areas and the transformation of relief under increasingly strong anthropogenic pressure has long been studied in Poland and other parts of the world (Śnieszko, 1985; Kruk et al., 1996; Kruk and Milisauskas, 1999; Brown, 1997; Dotterweich, 2008; James, 2013). Nevertheless, it remains challenging to distinguish the influence of natural factors from anthropogenic ones (Starkel, 2005, 2006; Kołodyńska-Gawrysiak et al., 2017) as both can affect the evolution of the landscape and trigger gully formation processes (Valentin et al., 2005; Dotterweich et al., 2012; Twardy, 2013).

This study investigates the relationship between agricultural activity and changes in geomorphic processes in the loess areas of southwestern Poland. The study specifically focuses on gullies located in the forested areas of the Sudetes Foreland, areas where little information is currently available about their age, spatial distribution, and morphological and topographical characteristics. The chronological studies are primarily based on Optically Stimulated Luminescence (OSL) dating of the deposits filling the gully. However, it is important to note that during the colluviation process, the OSL signal may not always be fully reset, requiring a cautious interpretation of results that considers sedimentary characteristics, geomorphological conditions, and other factors (Poręba et al., 2012, 2013).

Within the research conducted, the chronology of colluvial deposits filling the bottom of the gully was established by OSL dating. The study also constrained the extent to which particular factors played a role in triggering the gully processes. This research allowed us to identify the historical causes of gully erosion, particularly determining whether the main periods of gully erosion in Europe were associated not only with deforestation and land overuse but also with periods characterized by frequent extreme rainfall events (Lang and Mauz, 2006). In addition to OSL dating, other methods such as ^{14}C (radiocarbon) and fallout radioisotope dating were also used in this study. Cs-137 is a valuable tracer of modern sediments and is used in various environments to study erosion and sedimentation processes (Porto et al., 2003; Knox, 2006; Poręba et al., 2018)

Therefore, to achieve the research objectives, multiproxy methods were utilized, including geomorphological, lithological, and various geochronological analyses.

STUDY AREA

The research was carried out in the loess areas of the Sudetes Foreland in southwestern Poland, where loess is predominantly found as isolated patches. The study focused on the Strzelin Hills (Jary et al., 2002), a region characterized by longitudinal stretches of hills with elevations exceeding 300 m a.s.l., with the highest elevation at Gromnik 392 m a.s.l. The geological composition of the area includes gneisses, quartzite, mica schists, marbles and amphibolites (Oberc-Dziedzic and Szczepański,1995). The average thickness of the loess cover in the study area is ~3–6 m and includes a variety of typical landforms, including gullies. Of particular interest is a gully located near the village of Nowolesie (17.05 E/ 50.71 N; Fig. 1A) on the western slopes of the Strzelin Hills.

The entire gully system of the Strzelin Hills is currently covered by forest. The study involved an examination of sedimentary structures using boreholes and horizontal dug profiles of the deposits filling the bottoms of gullies in the Nowolesie area. Only one site, based on sedimentology and the condition of the gully, was deemed suitable for further excavation and detailed analysis, the results of which are presented in this paper. The gully analysed is situated on the northern slope of the Strzelin Hills, ~1 km south of Nowolesie village. This slope is dissected by three separate gully systems. The gully analyzed is ~500 metres long with several side branches. The gully's slope reaches an inclination of 53°, which decreases to between 10 and 20° at the mouth of the form (see Fig. 3A). The upper parts of the gully are V-shaped, with a distinct deepening at its bottom, indicating two-phase deepening. In the upper parts of the gully, erosive indentations in the bottom can reach 5 m in depth (see Fig. 3B–D). The lower parts of the gully have a flat bottom, as illustrated in Figures 3B and 3C. Excavation was carried out in this particular section of the gully. At the mouth of the gully, a currently inactive alluvial fan can be observed.

MATERIAL AND METHODS

The excavation, 5.5 m long and 4 m deep, was made using an excavator across the gully at its lower part (see Figs. 1B and 2A). The profile was cleaned to better distinguish the sedimentological variations (Fig. 2B). Samples for laboratory analysis were taken from each stratigraphic unit (Fig. 2C). Laboratory analyses were carried out primarily in the Laboratory of Soil Mechanics at the University of Wroclaw and included grain size analysis (*Mastersizer 2000*), and the determination of carbon/humus content employing the Tiurin method. The content of anthropogenic elements, specifically heavy metals such as Cu, Pb, Zn, Cd, Fe, Ni, Cr, and Mn, was also measured. For dating purposes, both OSL and radiocarbon ^{14}C dating methods were used. Additionally, ^{137}Cs analysis was carried out on samples taken from the upper layers of the succession. Both OSL and ^{14}C dating, as well as ^{137}Cs analysis, were conducted in the Division of Geochronology and Environmental Isotopes at the Institute of Physics CSE, Silesian University of Technology.

GRAIN SIZE, HUMUS AND HEAVY METAL ANALYSES

Twenty-nine samples were collected for grain size analysis. Samples were taken every 10 cm down to a depth of 2.6 m, and thereafter at 50 cm intervals. Laboratory determination of grain size was determined using a laser grain-size analyzer (*Malvern Mastersizer 2000*), which has a measurement range of 0.02–2000 µm with a precision of ~1%. The samples were prepared by removing impurities, including organic matter and carbonates, using 30% hydrogen peroxide (H_2O_2) and 10% hydrochloric acid (HCl) solutions. Subsequently, the samples were dispersed in a 0.5 N sodium metaphosphosphate ($(NaPO_3)_6$) solution and subject to ultrasonic sound for five minutes prior to measurement (e.g., Mason et al., 2003).

Organic carbon content was measured using the Tiurin method (Drozd et al., 2002). Soil mineralization and heavy metals were determinated according to standard EPA-3051 procedures. The soil samples were first dried, ground, and sieved.

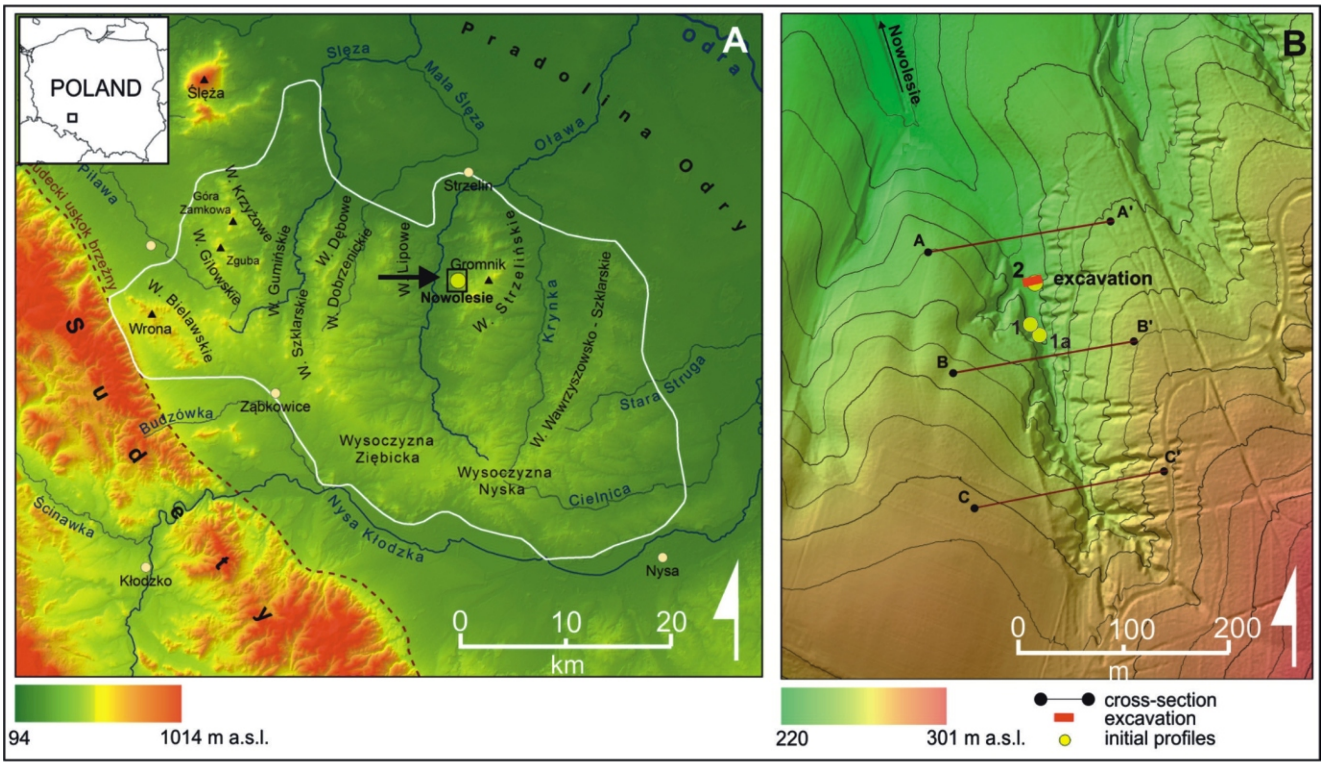

Fig. 1A – location of the study area within SW Poland and the Sudetes Forefield; B – detailed map of the Nowolesie gully with location of the excavation and cross-section profiles

Fig. 2A – excavating a sedimentary profile across the Nowolesie gully by using excavator; B – general view of sedimentary profile, C – taking OSL samples

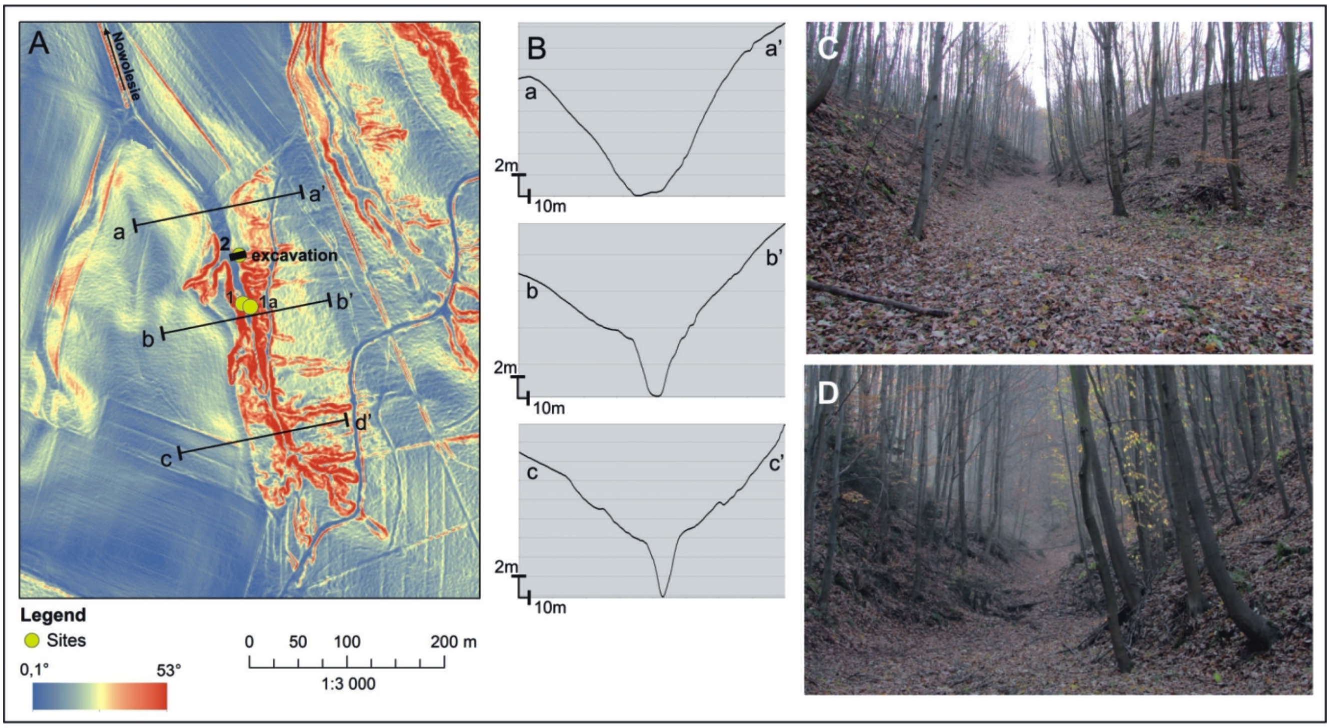

Fig. 3. Geomorphological characteristics of the Nowolesie gully

A – slope map derived from LiDAR data; **B** – cross-sections through the gully; **C** – flat-bottomed lower part of the gully; **D** – V-shaped upper part of the gully

Then, 0.5 g of each sample was treated with 5 ml of 60% ultrapure nitric acid (HNO_3) in a Teflon digestion vessel. The mineralization process utilized a *Mars X-PRESS* microwave mineralizer from CEM Corporation. After the mineralization process, the solution was diluted, filtered, and subjected to flame atomic absorption spectroscopy (FAAS) using an *Avanta Sigma* system from GBC for heavy metal analysis. The results obtained were adjusted to reflect the dry weight of the sample (EPA Method 3051,1990; Jakimowicz-Hnatyszak and Rubel, 1998).

OSL DATING

Eleven samples were analyzed in the Gliwice Luminescence Laboratory (GLL, Moska et al., 2021) using optically stimulated luminescence (OSL). To determine the luminescence age, both the equivalent dose and the dose rate need to be determined. The equivalent dose is determined by a luminescence reader after chemical preparation of quartz grains, while the dose rate is calculated based on the values of natural radioactivity in the samples (Moska et al., 2021). Furthermore, sediment samples from 3 cores were analyzed in the GLL to determine ^{137}Cs contents.

In the laboratory, samples were prepared both for gamma spectrometry and luminescence measurements. High-resolution gamma spectrometry using a HPGe detector was used to determine the content of uranium (^{238}U), thorium (^{232}Th) and potassium (^{40}K) in the samples. Each measurement lasted for at least 80 ks. Prior to activity measurement, all samples were dried and then placed in measurement containers (Poręba et al., 2020). To ensure accuracy, samples for radioactivity measurement were stored at least 4 weeks to achieve radioactive equilibrium within the uranium decay series. The activities of the isotopes present in the samples were determined using IAEA standards RGU-1, RGTh-1, RGK-1. To calculate the ^{238}U content, the following gamma lines were taken: 295.1 keV (^{214}Pb), 352.0 keV (^{214}Pb), 609.3 keV (^{214}Bi), and 1120.3 keV (^{214}Bi). For the ^{232}Th decay chain, the following gamma lines of 583.0 keV (^{208}Tl), 911.2 keV (^{228}Ac), and 2614.4 keV (^{208}Tl) were considered. The ^{40}K content was calculated using the 1460.8 keV gamma line. Dose rates were calculated using an online dose rate calculator (Tudyka et al., 2023), which contains all the latest conversion factors. Water content was assumed 15 ±5% for all samples. The method of Prescott and Stephan (1982) was used for the cosmic ray beta dose rate calculation. For OSL measurements, coarse silt-sized particles of quartz (45–63 μm) were extracted using standard chemical procedures (Aitken, 1998). First the sediment samples were treated with 20% hydrochloric acid (HCl) and 20% hydrogen peroxide (H_2O_2) to remove carbonates and organic material. Next, the quartz grains were separated using density separation with the application of sodium polytungstate solutions leaving grains of densities between 2.62 g/cm^3 and 2.75 g/cm^3. The grains were then sieved, before etching with concentrated hydrofluoric acid (HF) for 60 minutes. An automated Risø *TL/OSL DA-20* reader was used for the OSL measurements of multi-grain aliquots, each weighing ~1 mg. The stimulation light source was a blue (470 ±30 nm) light-emitting diode (LED) array delivering 50 mW·cm^{-2} to the sample, and detection was through 7.5 mm of a Hoya U-340 filter. Equivalent doses were determined using the single-aliquot regenerative-dose (SAR) protocol (Murray and Wintle, 2000). To determine the final statistical model of equivalent dose (De) for each of the samples, the overdispersion parameter for all distributions was calculated using the R package Luminescence” (Kreutzer et al. 2012, 2020).

The overdispersion parameter ($_{OD}$) refers to the spread in De values remaining after all measurement uncertainties have been taken into account. In other words, overdispersion in lumi-

Table 1

OSL ages for all samples investigated

Lab. code	Sample ID	Sampling depth [cm]	H_2O [%]	Th (Bq/kg)	U (Bq/kg)	K (Bq/kg)	Over dispersion [%]	Dose rate [Gy/ka]	Equivalent dose [Gy]	OSL Age [ka]
GdTL-3610	Nowolesie_1	400	15±5	45.2±1.0	44.2±1.3	669±51	19	3.53±0.16	36.7±1.8	10.5±1.0
GdTL-3611	Nowolesie_1a	400	15±5	47.5±2.2	42.7±1.3	631±48	11	3.44±0.15	29.7±0.8	8.8±0.7
GdTL-3612	Nowolesie_2	350	15±5	44.3±1.0	39.7±1.2	661±50	15	3.42±0.16	13.2±0.5	3.9±0.4
GdTL-3613	Nowolesie_3	305	15±5	55.0±1.1	41.5±1.2	640±49	34	3.57±0.16	13.5±0.6	3.4±0.4
GdTL-3614	Nowolesie_4	250	15±5	33.2±0.8	31.2±0.9	668±51	34	3.13±0.16	8.6±0.6	1.7±0.3
GdTL-3615	Nowolesie_5	190	15±5	59.6±1.2	45.9±1.3	537±41	26	3.46±0.14	11.1±0.4	3.0±0.4
GdTL-3616	Nowolesie_6	135	15±5	41.0±0.9	38.5±1.1	665±51	26	3.40±0.16	9.8±0.5	2.4±0.3
GdTL-3617	Nowolesie_7	110	15±5	34.7±0.8	33.8±1.0	666±50	41	3.23±0.16	1.36±0.07	0.40±0.05
GdTL-3618	Nowolesie_8	80	15±5	46.2±0.9	42.3±1.2	621±47	49	3.46±0.15	1.48±0.06	0.43±0.05
GdTL-3619	Nowolesie_9	58	15±5	38.0±0.9	35.9±1.1	666±51	26	3.35±0.16	11.8±0.7	2.7±0.3
GdTL-3620	Nowolesie_10	47	15±5	33.4±0.8	33.1±1.0	651±49	33	3.19±0.15	11.8±0.5	3.1±0.4

Laboratory code and sample ID with thorium, uranium and potassium concentration with dose rate. Overdispersion with equivalent dose and OSL ages obtained using the MAM or CAM model (Galbraith et al., 1999)

nescence dating refers to the observed variation in equivalent dose (De) measurements that exceed what would be expected based on purely statistical, measurement-related uncertainties. It represents additional variability in the luminescence signals from individual grains or aliquots of sediment. For samples with an overdispersion parameter lower than 20%, the central age model (CAM), Galbraith et al. (1999) was used. For samples with a non-unimodal dose distribution and higher overdispersion parameter, the minimum age model (MAM) was employed (Table 1). It may be assumed that during redeposition there was a problem with resetting the luminescence signal (insufficient exposure to sunlight; Poręba et al., 2013; Moska, 2019).

^{14}C AND ^{137}Cs DATING

A single layer including charcoal was sampled from the profile at the depth of 2.80 m. The radiocarbon dates were calibrated using *OxCal 4.3* (Bronk and Ramsey, 2009) using the *IntCal20* calibration curve (Reimer et al., 2020). The dark material from the 0.45 m layer has been identified as a type of slag, which is unsuitable for dating purposes. The dark material from the 0.45 m layer turned out to be unsuitable for ^{14}C dating purposes.

In addition to the samples for OSL dating, three cores were collected to measure the activity of ^{137}Cs. Two of these cores were collected several metres before the trench and one of them was from the immediate vicinity of the trench. In the laboratory, the cores were divided into 5 cm sections. After drying, they were prepared for activity measurements by semiconductor gamma spectrometry, similar to the samples intended for dose rate determination in OSL dating. The activity of ^{137}Cs in all samples was determined by low-background high-resolution gamma spectrometry analysis. The counting time was usually at least 80 ks, and IAEA (International Atomic Energy Agency) standard Soil-375 was used as a reference material for ^{137}Cs activity determination. The 661.7 keV gamma line was used to calculate the ^{137}Cs content.

RESUTS

LITHOLOGICAL PROPRIETIES

GRAIN-SIZE ANALYSIS

The material at the bottom of the profile has a periglacial origin and is a mixture of silt, sand, gravel, and clasts of bedrock gneiss. Above this, four horizons of galyic/fossil soils were found, separated by layers of loess colluvium. At depths below 4 m, the material is mostly composed of silt, sand, gravel, and bedrock gneiss clasts (Fig. 4A, B). At the depth of 2 m, there is a significant change in grain size, with the material becoming much coarser and sandier, and mixed with gravels. However, silt is still the dominant fraction in the colluvium, with occasional layers of sand (Fig. 4A, B). The accumulated material is noticeably coarser at a depth of ~20–40 cm.

HUMUS CONTENT

All values of measured humus content (Fig. 4C) ranged from 0.8 to 2.4%, which is notably higher than those typically found in homogeneous loess deposits, indicating that the material is likely redeposited, consisting of altered colluvium. The humus content begins to increase from a depth 1.20 m, shows a decrease at 0.8 m, and then clearly increases again between 0.70 and 0.40 m. Another increase is connected with the modern soil development.

HEAVY METAL CONTENT

The profile was analysed to measure the elements of anthropogenic origin in the samples, including the content of heavy metals such as Cu, Pb, Zn, Cd, Fe, Cr, Mn, and Ni. The diagrams (Fig. 5) show quite similar trend for all the elements. There is a first pronounced increase at a depth 2.60–2.80 m, especially Cr, Fe, Mn, and a decrease at 2 m. Other clear increases are at 1 m (Cd, Ni, Pb, Zn, Cu) and 60–70 cm (Cd, Ni, Pb, Zn). The Cu curve is relatively stable except for a peak at a depth of 1 m.

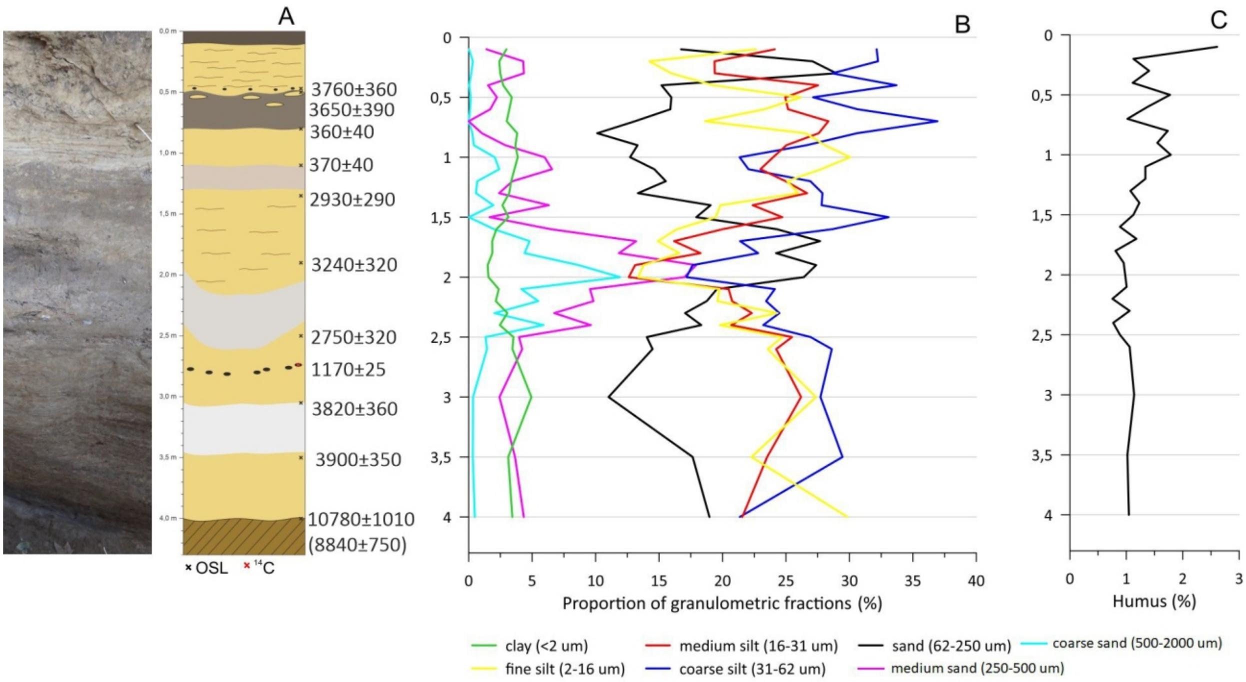

Fig 4A – Holocene sedimentary profile in the Nowolesie gully bottom with OSL and 14C dates marked; B – grain-size analysis; C – analysis of humus content

DEPOSIT CHRONOLOGY

OSL AND ^{14}C DATES

Eleven OSL dates and one ^{14}C date were obtained from the material taken from the profile (Table 1 and Fig. 6). The bottom OSL dates of 10.5 ±1.0 ka (GdTL-3610) and 8.8 ±0.7 ka OSL (GdTL-3611; Fig. 4A), located at the depth of 4.0 m, suggests the Pleistocene genesis of the erosive cut, and stabilization of the gully bottom in the early to middle Holocene. The age of this layer, according to OSL dating, is predominantly from the late Bronze Age. The first erosion episode, dated around 3.9 ±0.4 ka (GdTL-3612), likely occurred during the early period of Bronze Age. Below the erosion layer, loess diluvium with a thickness of 0.55 m was found, lying directly on periglacial deposits. The date of 3.4 ±0.4 ka (GdTL-3613) indicates brief slope stabilization and development of a soil cover with a thickness of 0.4 m, now at the depth of 3.10–3.50 m. Interestingly, at the depth of 2.70–2.80 m, a layer of charcoal was found within loess diluvium. Charcoal samples from this layer yielded a ^{14}C date of 1170 ±25 BP (GdA-5866). On the calibration curve for this result few local maxima occur but the final calibrated ^{14}C age, with three sigma probability, ranges between 770 and 990 AD (1070 ±110 calBP). Above this sampling point, between 2.70 and 1.10 m, is a massive loess diluvium level with older and inverted OSL ages (GdTL-3614, GdTL-3615, GdTL-3616). This mixed material, without clearly visible sedimentary layers, was probably trapped in temporary sinks along other tributaries of the gully and moved in masses/packages later during erosive events (Early Middle Age, Industrial Revolution, modern times; Teisseyre, 1994). Such a mode of sediment transport in the gully significantly reduces the probability of resetting the luminescence signal during redeposition, as indicated by the wide distributions of equivalent doses for samples analysed from this

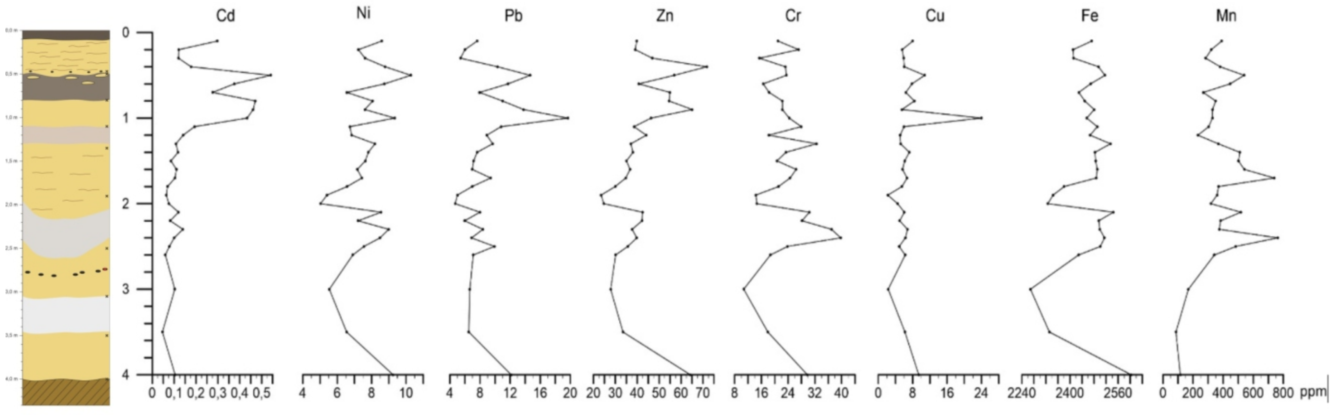

Fig. 5. Heavy metal content in the profile of the Nowolesie gully

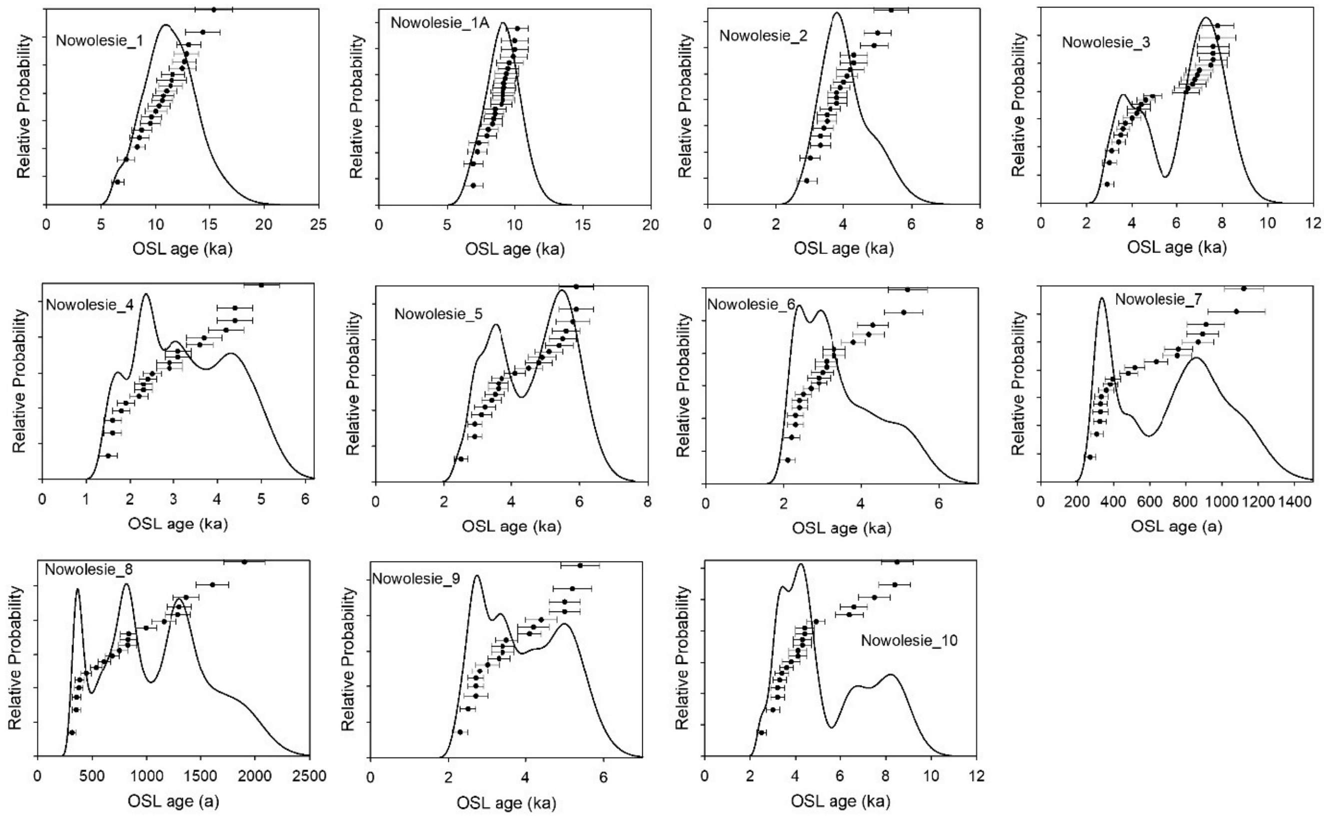

Fig. 6. OSL age results and probability density functions for all 11 samples described in this study

area. Above this, between 1.10 and 0.80 m, another loess diluvium level was found, but the results obtained are much younger, around 400 ±40 years (GdTL-3617 and GdTL-3618). Both samples are characterised by very wide distribution and high value of overdispersion parameter. Above this layer, alternating soils were discovered. While no charcoal was found for radiocarbon dating, some archaeological artefacts from the 19th century were found. The topmost half-metre of sediment was likely redeposited in the 20th century. However, the luminescence results suggest that during redeposition conditions did not allow resetting of the luminescence signal, so the final results are highly overestimated, oscillating around 3 ka (GdTL-3619 and GdTL-3620).

^{137}CS ANALYSIS

The patterns of the results of ^{137}Cs activity measured in the sedimentary profiles investigated show similar characteristics. In all three cases, the maximum activity was observed at a depth greater than 20 cm, which ranges from 6.32 ±0.83 to 19.45 ±0.95 Bq/kg, while the ^{137}Cs activities measured above are significantly lower (Fig. 6). The results obtained for all three cores indicate that these locations are not solely characterized by ^{137}Cs deposition from the atmosphere, as shown by the depth distribution of activity (e.g., Poręba et al., 2019). Analyzing the ^{137}Cs activity values in the profiles examined suggests that these sites are neither characterized by simple accumulation of material eroded in the valley nor by "pure" erosion. In the first case, there would be a superposition of material with varying erosion-related specificities and caesium activity, while in the second, some part of the caesium would be simply removed from the profile. Therefore, it can be concluded that for all the profiles tested, the ^{137}Cs originally deposited from the atmosphere was removed, and then accumulated as ^{137}Cs-containing material eroded from the upper parts of the valley, likely with a significant contribution of material from linear erosion. It appears that the material was accumulated after 1986, i.e. after the Chernobyl nuclear incident, which led to increasing deposition of ^{137}Cs.

CERAMIC ANALYSIS

At a depth of around 60–70 cm in the fossil soil, pieces of ceramic estimated to be 100 years old were found. This suggests that when the gully was stabilized and covered with vegetation, people from the nearby village of Nowolesie used it as a dumping ground for rubbish. This finding also confirms the real age of this fossil soil, which is estimated to be between 100 and 150 years old.

DISCUSSION

The data presented reveal environmental changes in southwestern Poland based on the bottom deposits of the Nowolesie gully. The results obtained can be combined with the known settlement history and other archaeological data to reconstruct the evolution of the gully studied. The gully underwent several phases of infill. The data suggest that initial cycle of gully filling by colluvial deposits occurred at the beginning of the late Neolithic and early Bronze Age. This aligns with archaeological research indicating high settlement intensity during this period (Lisowska, 2017).

The increase in human activity during the late Neolithic and early Bronze Age, as indicated by the OSL dates of Nowolesie 2 (GdTL-3612) and Nowolesie 3 (GdTL-3613), was associated with deforestation and rapid deposition of slope material at the bottom of the gully. Following the Neolithic/Bronze Age period, vegetation re-established and stabilization of geomorphic processes occurred until the Middle Ages. This is supported by the layer of charcoal which was dated to 1070 ±110 cal BP. On top of the charcoal layer, a mixed layer of colluvial loess deposits was found, dated to 1.7 ±0.3 ka and 3.0 ±0.4 ka OSL, suggesting increased erosion during Medieval time, of sediment accumulated during the Bronze Age. It is possible that this material was trapped in temporary sinks in the gully and/or other gully branches and later transported in masses/packages during erosive events from the early Middle Ages to modern times. Hillslope sediments are typically eroded, transported, and accumulated not in a single event, but temporary storage on the hillslope occurs before further mobilization takes place (Fuchs and Lang, 2009). The transport of material from the source to temporary sinks and later to the gully bottom is similar to the scheme described by Lang and Hönscheidt (1999). However, the details of this process associated with human impact need to compared with the records of other gullies in SW Poland. An exception is the erosive horizon from 0.80–1.10 m, which likely occurred during the 14th century humid period, preceding the onset of the Little Ice Age (Maruszczak, 1988). It has been observed that strong soil and gully erosion occurred in southern and central Germany during the latter half of the 14th century, a time when erosion reached its peak levels (Bork et al., 1998; Lang, 2003; Dotterweich, 2008). According to Bork (1989), the 14th century marked the most significant period of gully erosion in Germany in the second millennium, resulting from extreme precipitation and considerable deforestation during the 13th century colonization under Magdeburg law. In Eastern Central Europe, colonization predominantly occurred in the 14th century. Gully erosion in Slovakia was also noted during the 14th century (Stankoviansky, 2003). In southeastern Poland, particularly within the sub-Carpathian loess plateau, in Roztocze (Śnieszko, 1995; Schmitt et al., 2006), and on the loess of the Proszowice plateau (Poręba et al., 2019), strong slope erosion was similarly observed during this period.

The radiocarbon date of charcoal, 770–990 AD (GdA-5866), may suggest intensive land clearance (burning wood) by Slavic tribes in this area during the Early Middle Ages (Kulczycka-Leciejewiczowa, 1993). Nowolesie village was first mentioned in 1331 AD and Witostowice in 1290 AD (Lisowska, 2017). Settlements in this region were insular, located close to rivers, on fertile soils up to 300 metres from the riverbanks. The Funnel Beaker settlement type is difficult to reconstruct in this area (Kulczycka-Leciejewiczowa, 1993). However, the first people were not interested in settling or farming on the Strzelin Hills, but were only coming to exploit raw materials (Kulczycka-Leciejewiczowa, 1993). At the beginning of human settlement in the area, anthropogenic changes of the natural environment, such as deforestation, slope and soil erosion and water regime, were not strong, and human interference in the surrounding area was weak and quickly regenerated. Settlements along the Oława River were scarce, in contrast to the Glubczyce Plateau, which had more settlements, likely due to the mountain character of the rivers with frequent floods and periodic flooding (Zygmunt et al., 2006; Zygmunt, 2009; Poreba et al., 2012). Unlike in other loess areas of Poland near the Moravian Gate or the eastern Sudetes Forefields, where the first agricultural cultures appeared from ~6.0 ka BP to 5.5 ka BP (Kulczycka- Leciejewiczowa, 1993; Kruk and Milisauskas, 1999), no clear traces of early Neolithic activity have been found in this area. However, the colonization of Europe during the Neolithic period, characterized by settled lifestyle, farming, and animal husbandry, was a gradual process that started in the south and progressively spread northwards, coinciding with global warming (Kruk et al., 1996, Kruk and Milisauskas, 1999). People migrated from the south through the Moravian Gate and other passages within the Sudetes and the Carpathians, in search of fertile soils and new areas for cultivation. Deforestation and land use resulted in increased soil erosion (Śnieszko, 1985). Anthropogenic changes have been observed mainly on loess plateaus of southern Poland (Kruk et al., 1996). Deluvial deposits, mostly formed as alluvial fans, can be found in systems of small dry valleys as a result of anthropogenic activity from the Neolithic period (Zygmunt et al., 2006; Zygmunt, 2009, Superson et al., 2014). In the resulting forms and settlements, one can often find a record of changes in the use of land by humans. Sedimentary structures and soil levels contain a record of temporal and spatial transformations of relief (Dotterweich et al., 2012). However, recognizing the impacts of Neolithic land clearance and agriculture is complicated by variations in climate, but general patterns concerning interactions between the impacts of land clearance and climate change are beginning to emerge. For example, slope deposits tend to record local human land-use changes, whereas the alluvial stratigraphy of larger rivers tends to initially record climatic events (Houben et al., 2006; Dotterweich, 2008).

The spread of Neolithic farming was closely associated with local clearing around settlement sites, where there was a notable shift in the dominant pollen to weeds and grain (Godlowska et al., 1987; Brown, 1997). The geomorphic responses to these clearings initially led to localized erosion and sedimentation. Significant fluvial overbank deposition began at a later stage. Lang (2003) describes a general model in which deliveries of anthropogenic sediment to larger floodplains in central Europe did not commence until the Iron Age and Roman occupation. However, based on a statistical analysis of ^{14}C dates throughout Germany, Hoffmann et al. (2008) conclude that floodplain sedimentation in central Europe started somewhat earlier, around 2.5 ka BP during the Bronze Age. This period coincides with population growth, extensive land-use changes, slope erosion, and episodes of climate change. The intensity of agricultural activity and its morphological impacts on the loess regions of Europe were particularly strong during the Bronze Age. The degree of these changes varied, being less pronounced during the Neolithic, Bronze, Iron, and Little Ice Ages, and more significant during the Middle Ages and Industrial Era. This variability was also observed in the region investigated (Superson et al., 2016).

During the 3rd period of the Bronze Age (3.3 ka BP) to the beginning of the Iron Age (2.4 ka BP), the Lower Silesia region was inhabited by people of the Lusatian culture. The cultural advances during this time are reflected in the many forts erected in the area, including the stronghold in Witostowice, which was first established during the Lusatian culture and later in the Middle Ages (Lisowska, 2017). The second object associated with the Lusatian culture in the literature of the 20th was the putative defensive foundation at the top of Mount Gromnik (Kaletyn, 1964; Kaletynowie and Lodowski 1968).

The interpretation of the results obtained is complex. At the bottom of the profile shown in Figure 4, the OSL dates may be associated with the period of valley formation.

Above this, there are gully deposits, likely synchronous with the erosion initiated in the Neolithic. The colluvial (slope) depos-

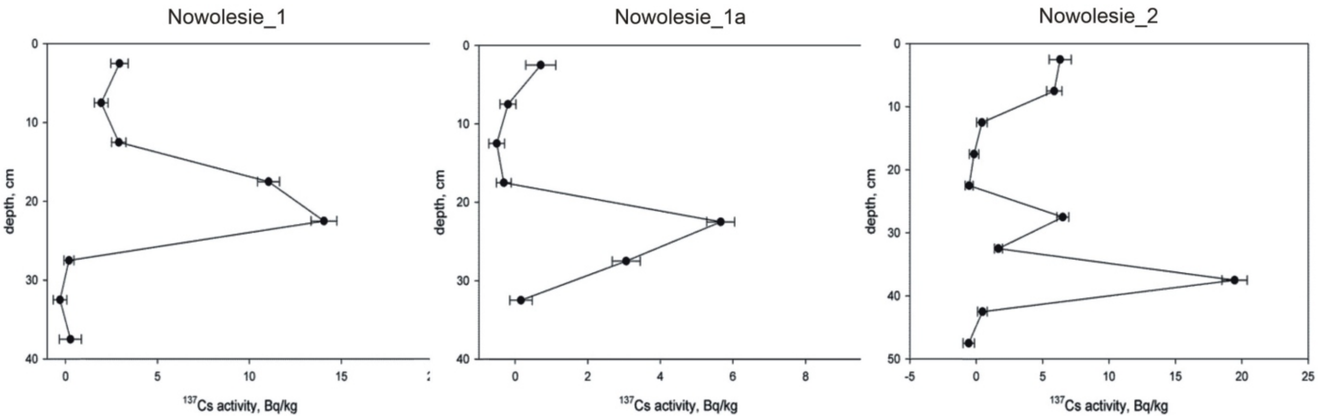

Fig. 7. Activity of ^{137}Cs in the upper part of the Nowolesie gully profiles (Nowolesie 1 and 1a) and close to the exposure (Nowolesie 2)

its are well-dated, spanning modern, medieval and Neolithic times. The problem occurs with the gully deposits (proluvium), where the date is the result of the source material's age and ineffective bleaching of previous luminescence signal during sedimentary transport. In cases such as the gully erosion at Szyczyce, Biedrzykowice and Bronocice (Poręba et al., 2013, 2018, 2019), transport did not facilitate significant bleaching, preserving the source material's age. Consequently, this deposit above mostly reflects Neolithic soil erosion sediment, redeposited here around the Middle Ages during the period of increased human agricultural activity in this area. The dates are "Neolithic" because the OSL signal was not reset during redeposition. Examining the dates and their distributions (Fig. 4), the original date of sediment has essentially been preserved. The variation in dates and their somewhat inconsistency vis-à-vis depth result from different deliveries of primary deposit trapped temporarily in sinks in upper parts of the gully (Lang and Hönscheidt, 1999). Therefore, the apparent inconsistency between the OSL and ^{14}C dates is misleading. The primary concern is that the ^{14}C date is over 1100 years BP, while a somewhat younger ^{14}C date from the 13–14th century was anticipated. At ~1.5 m depth, the grain size suggests potentially higher flow dynamics, with an increase in coarser grains. Above this, there is a deposit dating back several hundred years, likely accumulated during the Middle Ages. The dates and their distributions in Figure 6 indicate a possible last contact with light, yet the sediment was also redeposited. The grain size is slightly finer, suggesting that the runoff may have been gentler than before, allowing the sediment to bleach at least partially during redeposition. In this layer (1.5–0 m depth), the content of heavy metals (Fig. 5), such as Pb, is increased. The darker layer between appears to represent some slight stabilization and something like a humus level. Above the youngest dates, there are two OSL dates that have essentially retained their original age, where the grain size has visibly increased (Fig. 4). On the other hand, the layer where these two samples were collected, from ~0.5 m depth, was added not earlier than ~60 years ago. Upon careful inspection, these samples showed a slight trace of caesium (Fig. 7). However, there are no samples with younger ages in the data distribution. This means that the sediments had to be in contact with ^{137}Cs-bearing layers; the caesium reached them by migration and was then redeposited, without the possibility of whitening the OSL signal, within an intensive, dynamic process and in conditions of limited exposure to sunlight. A large supply of ^{137}Cs took place around 1963 (test nuclear explosions), which then successively decreased, with a further large supply (Chernobyl disaster). The latter delivery was highly spatially variable. The upper part of the soil probably built up after Chernobyl, but we could not find a record of the primary deposition of ^{137}Cs from the atmosphere in the profiles studied. Thus, it can be concluded that the upper part was eroded and rebuilt. The intensification of agriculture is not a uniform process but rather an event-related process combined with intensive rainfall. In the case of this area, it is possible that the event was in 1997 (Malik et al., 2021). Based on the ^{137}Cs results from the profiles, the caesium peak indicates that ~40 cm of sediment has accumulated after 1986.

CONCLUSIONS

Our study has investigated the relationship between agricultural activity and geomorphic processes in loess areas of southwestern Poland.

OSL dating of the deposits filling gullies during or after their formation offered an opportunity to establish their chronology. The samples dated by OSL were partially unbleached, a phenomenon resulting from the nature of sediment transport. Nevertheless, the OSL method allowed the development of a chronology, albeit a complex one. Additionally, for the upper, contemporary sedimentary layer, the ^{137}Cs method was applied, providing additional information. Primarily, the ^{137}Cs method enabled us to ascertain that we are dealing with a contemporarily redeposited sediment, and also provided information about the dynamics of the erosion and accumulation processes. Utilizing a combination of multiproxy methods, including geomorphological, lithological, and geochronological analyses, we showed that the age of the bottom deposits suggests a Pleistocene origin of the dry valley. The initial phase of gully filling was then linked to human activities during the late Neolithic/Bronze Age, characterized by deforestation, slope wash, and land cultivation. After this period, human activity lessened, leading to slope stabilization and vegetation recovery. The next cycle of erosion and deposition began in the Middle Ages and has continued with varying intensity until the present. Sediments from the Neolithic and Bronze Age periods, initially trapped in the upper parts of the gully branches, were eventually transported to the lower parts of gully, contributing to its infill in several episodes.

The uppermost part of the sediment profile, ~0.7 m thick, correlates with erosion and accumulation over the past 200 years, as shown by the presence of 19th century ceramics and ^{137}Cs levels. Overall, our study highlights the complexity of interpreting environmental changes in dynamic landscapes, where many external factors can be difficult to isolate. The results of luminescence dating, although partly incompletely bleached due to the nature of sedimentary accumulation in the gully, allowed for the creation of a chronology of the succession filling the gully bottom.

The findings indicate that changes of geomorphic processes in the study area are strongly related to human activity, predominantly agriculture. The sequences of colluvial loess-palaeosoil discovered at the bottom of the gully showcase phases of intense human activity, marked by both accumulation and erosion, as well as periods of stagnation leading to soil formation.

The results obtained allowed us to reconstruct environmental changes over the Holocene, including various periods of erosion and accumulation at the gully bottom and the transport of sediment from slopes to the valley bottom. Our findings also suggest that there were phases of intensive human activity, as shown by the presence of colluvial loess-palaeosoil sequences.

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