

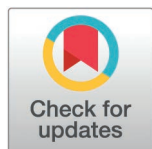
RESEARCH ARTICLE

What the landscape can tell: An integrative stratigraphic prospection approach to localize a Black Death mass grave in Erfurt/Central Germany

Michael Hein^{1,2,3*}, Nik Usmar², Annabell Engel⁴, Johannes Rabiger-Völlmer^{2,5}, Johannes Schmidt^{1,2}, Matthias Silbermann^{5,6}, Marco Pohle⁵, Iris Nießen^{1,7}, Martin Offermann^{1,2}, Lukas Werther^{7,8}, Birgit Schneider², Christian Tannhäuser⁹, Alexander Herbig¹⁰, Jan Nováček¹¹, Ulrike Werban⁵, Martin Bauch⁴, Christoph Zielhofer^{1,2}

1 Historical Anthropospheres working group, LeipzigLab, Leipzig University, Leipzig, Germany, **2** Physical Geography, Institute for Geography, Leipzig University, Leipzig, Germany, **3** Institute of Ecology, Leuphana University Lüneburg, Lüneburg, Germany, **4** Leibniz Institute for the History and Culture of Eastern Europe (GWZO), Leipzig, Germany, **5** Department Monitoring and Exploration Technologies, Helmholtz Centre for Environmental Research (UFZ), Leipzig, Germany, **6** Applied Near-Surface Geophysics and Remote Sensing, Institute for Earth System Science and Remote Sensing, Leipzig University, Germany, **7** Department for Medieval Archeology, Institute of Prehistory, Early History and Medieval Archeology, Eberhard Karls University, Tübingen, Germany, **8** Romano-Germanic Commission, German Archeological Institute, Frankfurt/Main, Germany, **9** Department for Cities, Thuringian State Department for the Preservation of Monuments and Archeology (TLDA), Weimar, Germany, **10** Department of Archeogenetics, Max Planck Institute for Evolutionary Anthropology, Leipzig, Germany, **11** Department of Anthropology, Thuringian State Department for the Preservation of Monuments and Archeology (TLDA), Weimar, Germany

* m.hein@uni-leipzig.de



OPEN ACCESS

Citation: Hein M, Usmar N, Engel A, Rabiger-Völlmer J, Schmidt J, Silbermann M, et al. (2026) What the landscape can tell: An integrative stratigraphic prospection approach to localize a Black Death mass grave in Erfurt/Central Germany. PLoS One 21(1): e0337410. <https://doi.org/10.1371/journal.pone.0337410>

Editor: Przemysław Mroczek, Maria Curie-Skłodowska University: Uniwersytet Marii Curie-Skłodowskiej, POLAND

Received: March 4, 2025

Accepted: November 6, 2025

Published: January 7, 2026

Copyright: © 2026 Hein et al. This is an open access article distributed under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Data availability statement: Geophysical (ERT) data has been uploaded to PANGAEA (<https://doi.pangaea.de/10.1594/PANGAEA.974818>). All other relevant data are within the paper and its [Supporting Information](#) files.

Abstract

The Black Death pandemic (1346–53 AD) caused a 30–50% population decline across Europe. For the city of Erfurt in Thuringia, substantial human losses and corresponding mass graves are well-documented in historical archives. The aim of our study is to localize these mass graves in the nearby deserted village of Neuses in order to validate the written sources and to obtain skeletal remains for future anthropological and archeogenetic analyses. Here we present our integrative approach of historical research and minimally-invasive stratigraphic and geophysical prospection. Within the area of interest, narrowed down by historical accounts and GIS implementations, we applied percussion coring and electrical resistivity tomography (ERT). Coupled geophysical and coring sections help elucidate the late Quaternary sedimentary processes as an essential natural background for more detailed geoarchaeological prospections. They allow to designate two distinct soil zones with consistent stratigraphical and pedogenic sequences: (1) a Chernozem zone and (2) a Black Floodplain Soil (humic fluvisol) zone. The distribution and extent of these zones co-determined the internal structure of the former village Neuses and the positioning

Funding: Fieldwork, analyses and personal funding was supported by the German Research Foundation (DFG) under the internal project number 464607492. The title of this project was “Climate, Famine, and Plague: A Pilot Study of the 14th-century Mass Graves of Erfurt from an Interdisciplinary Perspective”. Grant numbers of the three principle investigators are BA 5914/1-1 (Martin Bauch); WE 5518/3-1 (Ulrike Werban) and ZI 721/20-1 (Christoph Zielhofer). The funders did not play any role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing interests: The authors have declared that no competing interests exist.

of the presumed associated Black Death mass graves. Our approach enables a preliminary reconstruction of the medieval subsurface architecture, despite large-scale 20th century ground modification. We identified a belowground pit structure, visible in both, the borehole sequences and ERT sections. Recovered bones have been AMS radiocarbon-dated to the 14th century AD. Since confirmed and precisely-dated locations of Black Death mass graves are rare in Europe and are commonly found by chance during construction works, our systematic discovery of a possible plague pit may help to advance the research on the origin, spread and evolution of the *Yersinia pestis* pathogen throughout this pandemic as well as on societal coping mechanisms during epidemic outbreaks. Furthermore, our combination of methods holds the potential to successfully resolve the mapping of similarly demanding sites for archaeological and forensic investigations.

1. Introduction

The Black Death (1346–1353) at the onset of the Second Plague Pandemic, was the single most destructive disease in Eurasian history. Its demographic toll is estimated at 30 to >50% of the European population [1,2], albeit with considerable regional variation [3]. Only quite recently, the bacterium *Yersinia pestis* was unambiguously identified as the causative agent of the Black Death. Rodent populations are thought to have acted as the resident hosts for *Yersinia pestis* before the spillover to humans occurred mainly via infected fleas [4,5]. The pandemic originated in Central Asia in the first half of the 14th century [6,7] and found its way to Western Eurasia through the Black Sea region and Mediterranean harbors, likely disseminated along cereal trade networks [8–10]. It is still a matter of debate, whether and to what extent the emergence and the transmission of the pathogen were affected by climatic conditions [4,11]. The Black Death was only the first wave of the Second Plague Pandemic, however, and the disease periodically returned to the European scene for centuries afterwards [12,13]. While the genetic variety of *Y. pestis* was initially low during the Black Death, the bacterium diversified into multiple strains during the course of the Second Plague Pandemic [14–16]. It is currently under discussion, whether the plague was reintroduced to Europe in the following waves [11,17] or reemerged from Central European reservoirs and then spread in concentric waves across the continent [18]. With aDNA evidence drawn from investigations near Halle/Saale [19] and historical sources for Frankfurt and Thuringia [20], Central Germany is one plausible candidate region for hosting such reservoirs.

It is, however, equally true for Central Germany as for most other regions, that the vast majority of information on the Black Death is taken from documentary evidence that is provided by qualitative and quantitative historical studies [2,17,20], whereas archeological material and complementary chronological data remain comparatively sparse [3,21]. Historical sources imply numerous mass graves for plague victims dispersed throughout Europe [22,23]. Yet, to our knowledge, there are altogether less than ten excavated European mass grave sites for which archeological and

documentary evidence allow for precise dating to the period of the Black Death and positive identification of *Y. pestis* were presented. Among them are Saint-Laurent-de-la-Cabrerisse and Toulouse/France, London East Smithfield, Hereford Cathedral and Thornton Abbey/England, and Barcelona/Spain [16,21,24–28], with the best-researched and most precisely-dated of these arguably being East Smithfield [25]. For a couple of further mass grave sites with reference to the Black Death, such as Bergen op Zoom/Netherlands, Lübeck and Manching/Germany, as well as Kutná Hora/Czech Republic, either the chronology is still rather vague or the recorded mass fatalities were not unambiguously caused by *Y. pestis* [26,29–31]. Apart from an undisputed potential for archeogenetic and anthropological studies, the very existence of a mass grave is a crucial piece of evidence for historical sciences as it testifies to a society that fell into disarray for its inability to bury the victims during an abrupt mortality crisis [23,32,33].

The significant scientific value of Black Death mass graves and their sizable numbers attested in historical sources stand in harsh contrast to their low archeological representation. Hence, the exploration of undiscovered sites is imperative, not only to expand the immediate data base, but also their mapping and delineation can facilitate sustainable heritage management (cf. 34). By default, mass burials associated with the Black Death tend to be discovered by chance during construction works [25,26,29,34]. Well-established geophysical methods, such as Electrical Resistivity Tomography (ERT) and Ground-Penetrating Radar (GPR), are often subsequently applied to characterize these features and to determine their extent [21,35]. Systematic surveys for unmarked mass graves are, however, relatively rare in this archeological context (but see [36,37,38]). Complementarily, a lot of research has been done on the detection of recent, i.e., clandestine mass graves for evidential and forensic reasons, as reviewed in Hunter and Cox [39]. For such investigations, a stepwise approach is regularly used including (i) a map- and remote sensing-based background analysis, (ii) terrestrial reconnaissance utilizing a combination of several geophysical methods (e.g., ERT, GPR and fluxgate gradiometry), and eventually (iii) more extensive on-site investigations with excavations (cf. [40–44]). The morphological visibility of older mass graves in their landscape might often be negligible or blurred through time, so that subsurface analysis is usually the only way for their detection. Conveniently, the backfill of a mass grave is likely to stand out from its environment by differences in texture, color, moisture, elemental and organic matter contents, or some combination thereof. For that very reason, it can be detected, e.g., by geophysical methods [33]. In spite of these unique sedimentary properties, soil mapping and sediment coring to unravel the natural stratigraphy of the surroundings and to compare it with potentially deviating structures is not a common part of a systematic prospection concept for mass graves, historical or otherwise. However, we argue that this kind of stratigraphic exploration should be an integral component to locate mass graves and similar subterranean features, at the very least in order to facilitate optimal interpretation and contextualization of geophysical results.

In case of the city of Erfurt, a major medieval urban center, particularly good prerequisites exist to combine methods of historical, archeological and geophysical research: According to a contemporary local chronicle, the Black Death began in the summer of 1350 AD [20], killing thousands of the inhabitants. Most of the dead were buried in eleven ditches in the parish churchyard of Neuses, a village some kilometers outside the city [45–47]. Construction of Erfurt's first airfield in 1926/27 AD uncovered partial remnants of the former parish church along with one mass grave [45]. Unfortunately, the documentation of this excavation, and particularly the location details, is rather inconclusive, not least because geographic coordinates are missing (Suppl. Section 2 in Supplementary Information [S1 File](#)). It only exists in fragments in local archives and none of the skeletal remains are preserved.

Here we present the results of our multi-phased and comprehensive survey strategy to detect and characterize the Black Death mass grave(s) of Erfurt/Neuses using combined geophysical and soil-stratigraphic prospection methods. Our objectives were to 1. narrow down the suspect area of the presumed Black Death mass graves; 2. explore the natural stratigraphic and pedogenic setting by means of sediment coring and geophysical surveys to generate a broader contextual understanding of the site; 3. specify the best-suited geophysical methods for the detection of a mass grave and characterization of the natural background alike; 4. supplement the existing historical and preliminary archeological record with independent chronostratigraphic evidence; and 5.

locate the mass grave(s) as a prerequisite for a future excavation and further archeogenetic and anthropological investigations.

2. Study area

2.1. Natural setting

The city of Erfurt (50°59'N, 11°2'E) is situated in Central Germany ([Fig 1A](#)), within the southern part of the Thuringian Basin ([Fig 1B](#)). Shales and mudstones from the Upper Triassic (Keuper) generally dominate the interior of the Thuringian Basin, producing gently undulating landscapes [48]. The area of interest (AOI: [Figs 1C/D](#)) is positioned on the southeastern footslope of the hill “Roter Berg” (“Red Mountain”), a prominent erosional remnant made up of mainly reddish shales and mudstones from the Middle Keuper (Norian Stage in the Upper Triassic Epoch) surrounded by fluvial gravels of the Weichselian (Upper Pleistocene) Lower Terrace in a wide Pleistocene valley of the River Gera. On the hill’s flat summit, a small veneer of highly-weathered fluvial gravels related to the late Elsterian Upper Middle Terrace is preserved. The vertical distance between the two terrace surfaces amounts to ~50 m. In some areas, the Lower Terrace bears a ca. 2 m thick cover of loess and loess derivatives, in which chernozem-like soils developed during the Holocene. Where this loess cover is missing, especially south and southwest of the “Roter Berg”, loamy soils formed by weathering of the Lower Terrace gravels [48] ([Fig 1C/D](#)). In these loess-free areas of the Lower Terrace positioned in the southern part of the AOI, wetlands existed at least until the 19th century, and former peat cutting is documented (Suppl. Section 1 in Supplementary Information in [S1 File](#)).

The potential natural vegetation of the area consists of *Fraxinus-Carpinus* to *Tilia cordata-Fagus* forest, depending on the kind of substrate [49]. Today, the study area has a roughly three-part structure in terms of vegetation cover ([Fig 2](#), Suppl. Fig 3 in Supplementary Information in [S1 File](#)). Its northern part is used for agriculture with dominant wheat and rapeseed cultivation, the middle part features a dense, partly spontaneous forest with *Populus*, *Acer*, *Sambucus* and *Prunus* species, while the southern part is occupied by a sports facility. Due to its shielded topographic location in the Thuringian Basin, Erfurt has low overall precipitation values of 530 mm/a with a pronounced summer maximum, and an average annual temperature of 9°C. According to the Köppen-Geiger classification, the region is located within the Dfb climatic zone [50,51].

2.2. Archeo-historical setting

A first reference to the existence of plague mass graves in the deserted village of Neuses at the foot of “Roter Berg” is given in the *Chronicon Sampetrinum* [46], a chronicle which covers the history of the St. Peter’s Monastery in Erfurt from 1072 to 1355 AD and is hence considered a contemporary source of local information [52]. The chronicle describes the overflow of Erfurt’s parish cemeteries with the outbreak of the Black Death and the advice of academics to dig ditches outside the city instead; and it provides very specific information on the operating method: To accommodate the growing number of bodies, the cemetery of the nearby village of Neuses, probably still in use for the local parish, was chosen by official decree as an emergency burial site. There, between July 1350 and February 1351, “eleven pits were dug [...], into which around twelve thousand bodies of people were brought in wagons and carts. These were continuously transported, three or four at a time” [53]. Probably in the immediate aftermath, but at least since 1355, an annual commemorative procession was established on St. Mark’s Day (April 25th), leading from Erfurt to the Black Death mass graves in Neuses (20, footnote 57). This custom was upheld for several centuries and thus, both the cause of the mortality and the rough location of the graves were preserved in collective memory.

In 1926/27, large-scale ground modification and terrain levelling took place in the AOI for the construction of Erfurt’s first airfield ([Fig 2A](#); Suppl. Fig 3 in Supplementary Information in [S1 File](#)). On the northern margin of the prospective runway, traces of the medieval deserted settlement of Neuses were discovered and partly excavated.

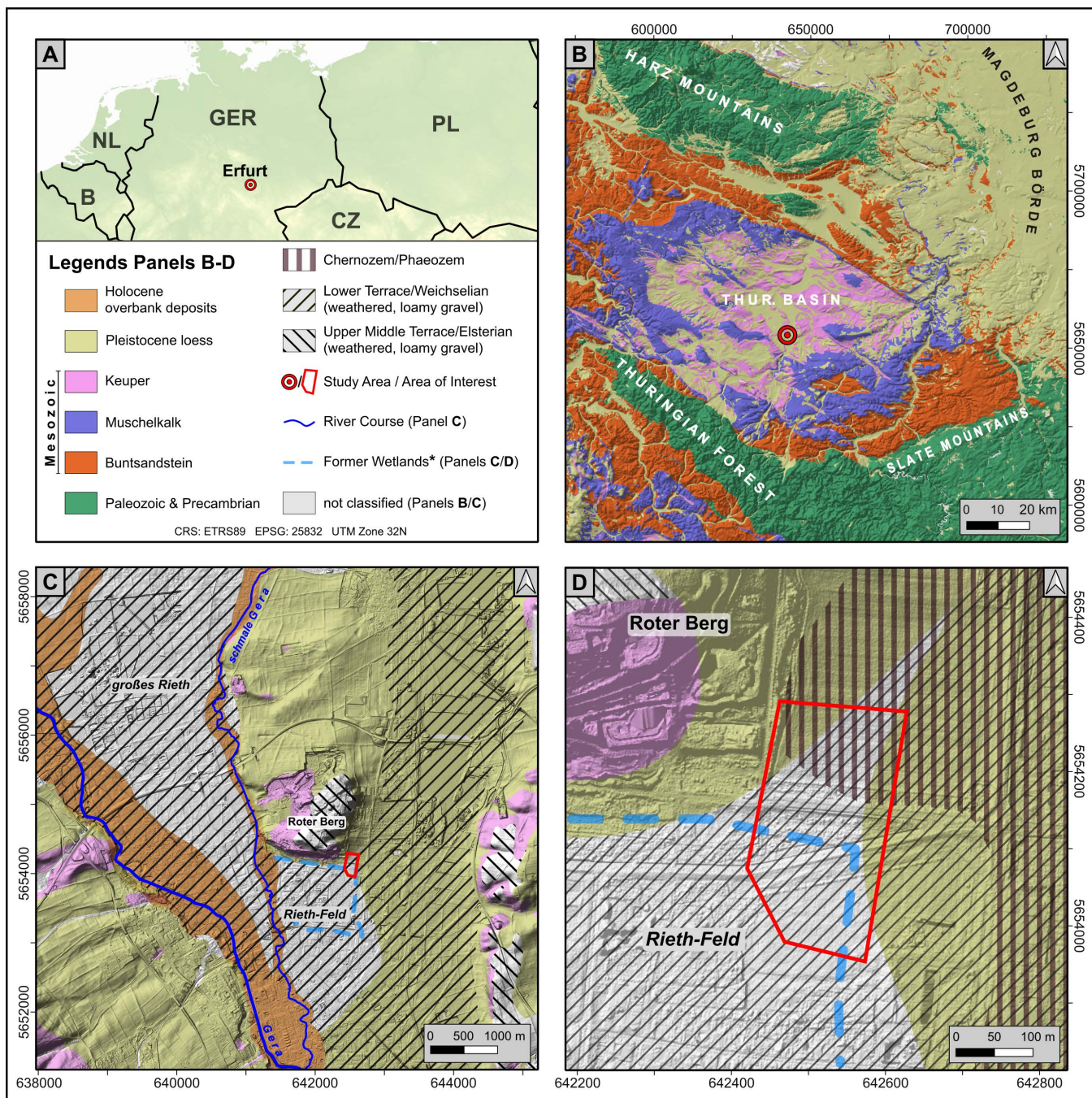


Fig 1. Geographical, topographic and geological overview of the study area. The position is given within (A) Central Europe, (B) the Thuringian Basin, (C) within the wide valley now partially occupied by the river Gera and (D) at the SW footslope of the hill “Roter Berg”. Topographic information in panels A and B obtained using open-access SRTM data with a 90-m resolution (www.earthdata.nasa.gov/sensors/srtm). For panels C and D, a LiDAR Digital Elevation Model DEM1 with 1-m resolution was used, kindly provided by the Thuringian State Office for Land Management and Geoinformation (©GDI-Th, License: dl-de/by-2-0, <https://geoportal.thueringen.de/gdi-th/download-offene-geodaten>). Geological information, according to the German Stratigraphic Commission taken from the Digital Geological Map GK25; pedological information taken from the soil map BGK 100. Both were kindly provided by the Thuringian State Office for the Environment, Mining and Nature Conservation (© GDI-Th, License: dl-de/by-2-0, <https://tlubn.thueringen.de/kartendienst>). *The rough area of former wetlands was deduced from older topographic and geological maps from 1839 and 1931, respectively (see Supplementary Section 1 in Supplementary Information in [S1 File](#)).

<https://doi.org/10.1371/journal.pone.0337410.g001>

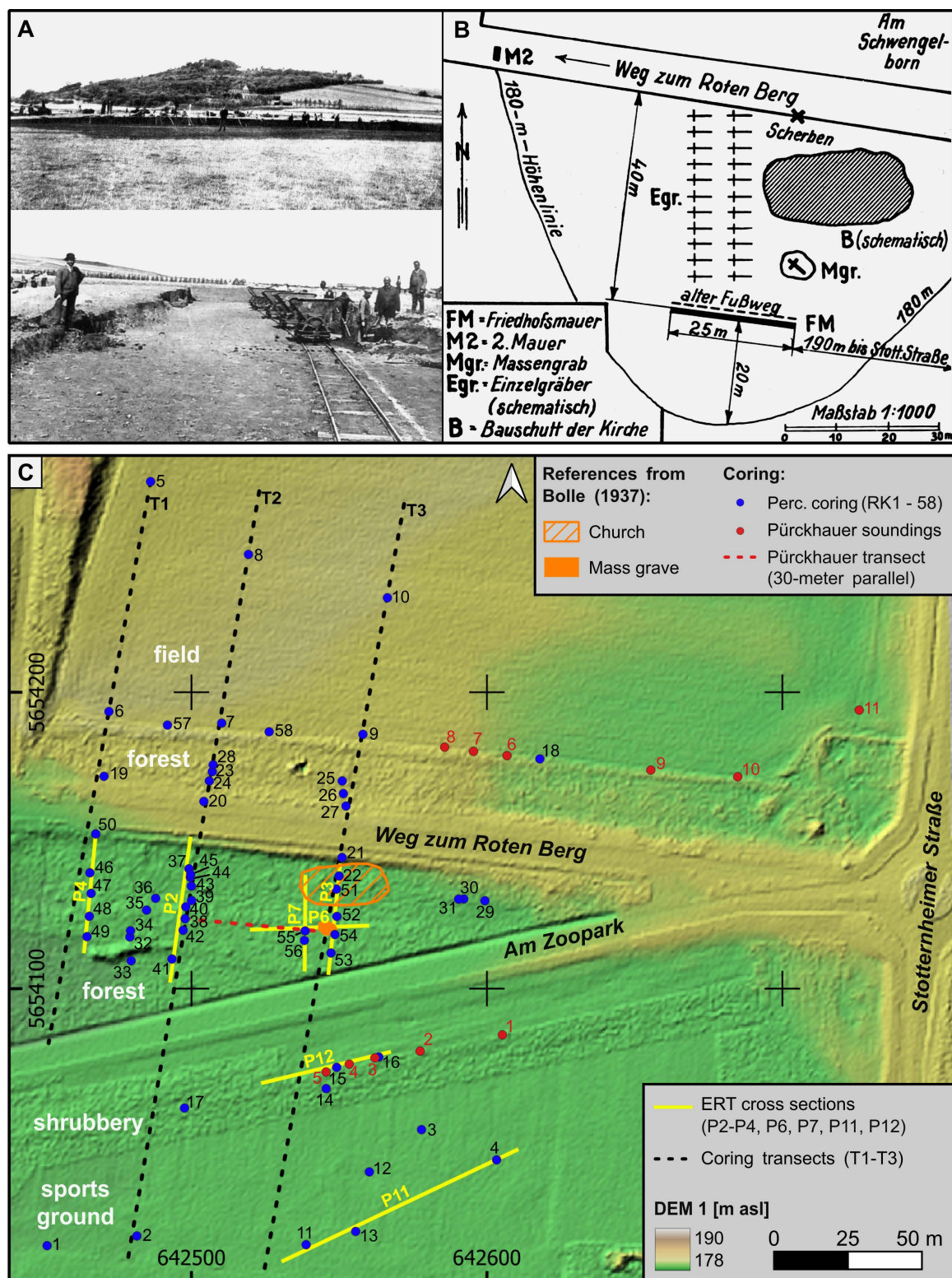


Fig 2. Graphical representations of the immediate study site. Panel A – Terrain levelling for the construction of the airfield in 1926 with the hill “Roter Berg” in the background (courtesy of Thuringian State Department for the Preservation of Monuments and Archeology TLDA; photo

credits: Wilhelm Lorenz 1926). Panel B – Map of the excavation findings 1926/27 (Bolle, 1937). For location, the map includes a scale (lower right = “Maßstab”) and the directional distances to the nearest roads. Abbreviations: FM = cemetery wall, M2 = second wall, Mgr. = mass grave, Egr. = individual graves (schematic), B = debris of the former church (schematic). Additional terms: “Scherben” = pottery sherds found at the northern edge of the excavation, “alter Fußweg” = former footpath, “180-m-Höhenlinie” = 180 m contour line, “190m bis Stott. Straße” = distance to the road ‘Stotternheimer Straße’. “Am Schwengelborn” refers to a toponym translating to ‘well sweep’. Panel C – Digital elevation model of the study area that displays all coring positions and the trace of all ERT-profiles included in the study (P2-P4, P6, P7, P11, P12). Also indicated in orange is the tentative position of notable features from the excavation in 1926/27 according to our preferential georeferenced version of the sketch by Bolle (1937), cf. Supplementary Section 2 in Supplementary Information in [S1 File](#). Current land use marked by white text boxes. DEM provided by the Thuringian State Office for Land Management and Geoinformation (© GDI-Th, License: dl-de/by-2-0, <https://geoportal.thueringen.de/gdi-th/download-offene-geodaten>).

<https://doi.org/10.1371/journal.pone.0337410.g002>

These results were presented alongside historical source studies in two publications by Bolle [45,54]. The findings include the former churchyard with individual graves as well as the presumed debris of the former parish church and remains of the southern cemetery wall. A 1.50 m by 1.50 m test pit on a slight hillock within the excavation area revealed a mass grave at 1.30 m below the surface, featuring human skeletal remains of ca. 20 individuals stacked upon each other without discernible organization or orientation, and apparently buried without a coffin. At a depth of 2.50 m, the excavation was suspended, although the bottom of this structure had not been reached. Based on the written sources, Bolle [45] related this archeological feature to one of the supposed eleven Black Death mass graves from 1350/51. Unfortunately, the current whereabouts of these skeletal remains are unknown, preventing their use for dating or other purposes. Therefore, a deviating chronology and cause of this previously-found mass grave cannot be excluded [32].

More recently, an archeological excavation was conducted prior to the construction of the road “Am Zoopark”, directly south of the 1926/27 excavation area, as depicted in Fig 2B. The main results of the excavation report [55] (internal TLDA procedure number VG-Nr.: 12/107) were summarized in a brief publication [56]. According to the findings, the road segment crossing our study area could be divided into (i) a western part with gravelly sediments that contained no archeological features and virtually no finds, and (ii) an eastern part with loess-like sediments, where numerous, mostly prehistoric loam extraction and storage pits were found. At the western margin of the loess area, remains of the deserted, medieval village of Neuses were discovered. Among them were a short double wall section, remnants of a half-timbered building and deep pits of unknown purpose, that contained pottery sherds of the 13th-14th century AD. No human bones or graves were found during this procedure.

3. Methods

3.1. Geospatial techniques for site reconstruction

The two reports on the preliminary results of the 1926/27 excavation also contain a sketch reconstructing the position of Neuses within the rural landscape [45,54], and a scaled map (Fig 2B) of the excavation area, which shows the locations of the churchyard, cemetery, and mass grave. Their spatial relationships and distances to adjacent roads and footpaths are also indicated. However, this map merely represents a vague starting point for the actual localization of the mass grave, because (i) the road network had partly been altered by the airfield construction and has evolved ever since, (ii) the excavation map lacks a coordinate system and the section is too small to clearly relate to any official roadmap of the time, (iii) much of the spatial reference in the map consists of archeological features that were eradicated by the excavation itself and (iv) the original report and documentation of the excavation activity have not been preserved, so that the map cannot be critically evaluated and adjusted.

For this reason, we attempted to georeference the map in ESRI Arc GIS (version 10) using the few spatial specifications still considered reliable in the excavation map [57], e.g., distances to roads that bear the same name today (see Supplementary Section 2 in Supplementary Information in [S1 File](#)). The preferential geographic positioning of the major elements of the map is presented in Fig 2 (Eastern variant in Suppl. Fig 2 in Supplementary Information in [S1 File](#)).

However, due to a scarcity of suitable control points on this map, we acknowledge that the easting (i.e., the accuracy on the west-east axis) remains a rather rough approximation. We further employed GIS to visualize the topographic data alongside the official geological and pedological information, and to display select findings of the 2012 archeological excavation [55,56]. Geophysical profiles and sediment cores attained during our fieldwork were levelled with a TOPCON differential GPS (DGPS; cm-scale horizontal and vertical accuracy).

3.2. Survey and prospection methods

The prospection for mass graves is generally considered to be challenging due to very specific sedimentary properties and dimensions that lead to highly heterogeneous geophysical responses [33,43]. For this reason, we applied an integrative combination of non-invasive and minimally-invasive survey and prospection techniques. Because of dense woody vegetation in large parts of the AOI (Suppl. Fig 3 in Supplementary Information in [S1 File](#)), an extensive surface coverage was not applicable for the geophysical surveys. The prospection strategy pursued a two-step approach. Firstly, ERT cross-sections and coring were carried out mainly along three approximately North-South-oriented transects T1 to T3 ([Fig 2](#)), carefully cut into the vegetation. Transects T2 and T3 were laid out to also intersect with the supposed position of the mass grave, depending on the respective variant of georeferencing of the excavation map made by Bolle ([45], see [Fig 2](#)); whereby we consider the eastern variant to be more robust than the western one (Supplementary Section 2 in Supplementary Information in [S1 File](#)). Intentionally, our geophysical and coring profiles extend well beyond the narrowed-down suspect area for the mass grave, allowing for a better characterization of the natural setting and hence a wider contextual understanding of the mass grave site (cf. [36]). Once this was achieved, we secondly made use of the fact, that in the old excavation map, the distance of c. 30 m from the supposed mass grave to the road “Weg zum Roten Berg” might be the most reliable element of spatial information ([Fig 2B](#)). However, we presume a spatial error of ± 5 –10 m for this specification to account for line thickness on the map, former measurement uncertainties, and possible changes in the exact position of the road’s southern edge – due to asphaltting and the renewal of roadside supply infrastructure since 1926/27 AD. Accordingly, our investigations were then turned to the parallel line 30 m south of the road, running roughly in a W-E direction, i.e., about perpendicular to most of the remaining profiles (red dashed line in [Fig 2C](#)). Field research was explicitly authorized by the City of Erfurt (written consent), and by private landowners/leaseholders (oral consent).

3.2.1. Near-surface geophysical methods. The application of geophysical methods is well-established for the detection and mapping of graves, where often a preference is given to electrical and electro-magnetic approaches [35,44,58]. Dense vegetation in the study area limited our investigations to linear transects, whereas 3D-surveys, e.g., electromagnetic induction methods (EMI) could not be performed. We focused on electrical resistivity tomography (ERT) that measures apparent electrical resistivity distribution in the subsurface with high vertical resolution. ERT is quite commonly used to investigate substrate variations [59] and, moreover, was successfully applied to map changes in bulk density caused by mass graves [35]. ERT profiles were measured with a PC-controlled direct-current resistivity meter system (Resecs II, GeoServe, Kiel, Germany). Electrode spacing was 0.5 m and transect length varied from 37 to 87.5 meters. [Fig 2C](#) shows the spatial layout of our ERT surveys. We chose a Wenner electrode array because of its low signal-to-noise ratio and appropriate vertical resolution to map the transects that mainly focus on the stratigraphical background (transects P2, P3, P4, P11, P12). Measurements for P2-P4 were performed in September 2022, after a very dry summer period had caused very low soil moisture, in particular in the topsoil. Transects P11 and P12 were measured in the beginning of June 2023 under moderate moisture conditions. For transects specifically aimed to image possible grave structures, following stratigraphic evidence from our cores, we applied Wenner- and additionally Dipole-Dipole electrode configuration for its higher lateral resolution. This applies to transects P6 and P7, measured in January 2023 under wet surface conditions. The data were processed and inverted using boundless ERT (BERT) software [60]. The maximum number of iteration steps was set to 20 for all inversions. Only profile P4 reached this limit, while all other inversions completed within 4–13 iterations. It should be noted that the inversion process is inherently non-unique.

Several variants of the inversion process were tested and the final selection was an informed decision based on data fit and pedological plausibility. We opted for L1 norm for inversion and the smoothing parameter was set to $\lambda = 20$ to $\lambda = 80$ according to the misfit parameters of the inversion. With these selected λ values, the relative root mean square error (RRMSE) for profiles P2–P11 ranges from 0.88% to 6.9%. Only profile P12 exhibits a higher RRMSE of 11.58% which can be attributed to the malfunction of one electrode during data acquisition. The chi-squared misfit values for all inverted profiles range between 0.66 and 3.96.

Ground-penetrating radar (GPR) was tested along several transects across the AOI [61]. Measurements were performed with an SIR-4000 (GSSI Geophysical Survey Systems, Inc., Nashua, USA) and antenna frequencies from 200 MHz up to 800 MHz (UtilityScan DF 300/800, 200 MHz and 400 MHz – Shielded Antenna, GSSI Geophysical Survey Systems, Inc., Nashua, USA). Due to a very high attenuation and a very low penetration depth [62], caused by the strong presence of clay (floodplain and slope sediments) in the first centimeters, it was concluded that GPR was unsuitable for our field site.

3.2.2. Pedomorphological survey. We conducted percussion coring (58 cores with ≤ 6 m depth, Fig 2C) to establish the natural pedological and stratigraphic background along transects, applying the soil catena concept [63]. We utilized an Atlas Copco Cobra motor hammer and several 1-m long stainless-steel gouges with a diameter of 6 cm for coring. Borehole sequences were documented in the field following the standards of German soil mapping and the World Reference Base for Soil Resources, WRB [64,65]. The descriptions comprise parameters such as bedding, texture, grain size, Munsell color, contents of organic matter, carbonates and clastic coarse fraction, redoximorphic properties as well as (anthropogenic) constituents such as pottery sherds, brick fragments and charcoal. In addition to percussion coring, Pürckhauer-type soil augers [66] were used for time-efficient subsurface prospection (henceforth: Pürckhauer). These 1-m long metal rods with 2-cm wide notches were driven into the ground by hand with a 3 kg plastic hammer. Pürckhauer sequences were not fully documented, because when stratigraphic deviations or anomalies were identified in these small cores, they were double-checked by percussion coring.

3.3. Dating approaches

3.3.1. Radiocarbon dating. Bone fragments and four additional charcoal pieces from the sediment cores were subjected to AMS ^{14}C dating at the Curt-Engelhorn-Zentrum Archäometrie (CEZA) in Mannheim (cf. Supplementary Section 4–5 in Supplementary Information in S1 File). The bones underwent collagen extraction (modified Longin method) and ultrafiltration was used to separate the fraction $> 30\text{kD}$, which was subsequently freeze-dried [67]. On the charcoal pieces, the ABA protocol (Acid-Base-Acid) was performed using HCl, NaOH and HCl to eliminate the most probable contaminants [68]. After pretreatment, the remaining sample residue was combusted to CO_2 in an elemental analyzer (EA) and the CO_2 was catalytically reduced to graphite. The ^{14}C content of the graphite was then measured applying a MICADAS-type AMS system. Simultaneously, $^{14}\text{C}/^{12}\text{C}$ and $^{13}\text{C}/^{12}\text{C}$ isotope ratios of samples, as well as calibration standards (oxalic acid-II), blanks and control standards were analyzed in the AMS. The determined ^{14}C ages were normalized to $\delta^{13}\text{C} = -25\text{‰}$ [69] and calibrated to calendar ages using the IntCal20 data set and OxCal software v4.4.2 [70].

3.3.2. Pottery-based chronological assessment. From the cores EN-RK 25, 27, 32, 35, 38, 46–48 and 57, we collected a total of 14 pottery sherds, mostly embedded within deposits that were classified as occupation and floodplain layers (Supplementary Section 3 in Supplementary Information in S1 File). The sherds were described with regard to the following optically analyzed characteristics: State of preservation, production technique, color, firing atmosphere, temper, hardness, surface texture and vessel type. Due to the strong fragmentation of all pieces, only a rough chronological classification could be made on the basis of the respective characteristics, since essential features, such as rim and vessel shapes were generally not identifiable. Categorization was based on expert knowledge and the relevant overview literature [71–73]. Further details can be found in the Supplementary Section 5.1 in Supplementary Information in S1 File.

3.4. Ethics statement and anthropological description of bones

The investigation of human skeletal remains was conducted under permit and ethical approval granted by the Thuringian State Department for the Preservation of Monuments and Archeology (TLDA). The TLDA is the competent authority with jurisdiction and legal responsibility for the protection, study, and curation of archeological human remains within the State of Thuringia. TLDA reviewed the research design and authorized the percussion coring, sampling, and scientific analysis of human bones in the form of written consent. As this study involves archeological remains of individuals deceased for several hundred years, informed consent from the individuals or their descendants is not applicable. Therefore, the requirement for informed consent was waived by the TLDA. Hence, all necessary permits, ethical or otherwise, were obtained for the described study, which complied with all relevant regulations. About 20 human bone fragments were recovered from eight bulk samples taken from sediment cores EN-RK 55 and 56. The bulk samples have received TLDA inventory numbers and were characterized with regard to species, skeletal region, approximate age-at-death and sex (see Suppl. Table 2 in Supplementary Information in [S1 File](#)). The bones are stored at the TLDA facilities in Weimar, Germany.

4. Results

4.1. Stratigraphy and soil geography of the study area

In terms of soil geography (henceforth: pedogeography), we divide the study area into a northeastern part and a southwestern part based on our investigations. These two parts show distinctly different near-surface depositional and pedogenic properties, which will be described in the following paragraphs: A 'Chernozem zone' and a 'Black Floodplain Soil zone', where the contact boundary of these two runs directly through the AOI. Standardized sequences and the main stratigraphic units (SU) for both zones are presented in the following paragraphs, as well as in [Table 1](#) and [Fig 3](#) (cf. Suppl. Sections 3 and 6 for detailed interpretation in Supplementary Information in [S1 File](#)).

4.1.1. Standard stratigraphies. The lowermost Stratigraphic Unit 1 (SU1) that we observed within the study area is a mudstone sequence from the Middle Keuper (Norian Stage). In the Chernozem zone, it is unconformably overlain by Stratigraphic Unit 2 (SU2), represented by fluvial gravels of the Weichselian Lower Terrace. This, in turn, is covered by a heterogeneous, loamy periglacial slope deposit, Stratigraphic Unit 3 (SU3). Following an erosional contact, Stratigraphic Unit 4 (SU4), a laminated slope-washed loess was deposited, which grades into a rather thin (15–65 cm) primary loess, Stratigraphic Unit 5.1 (SU5.1). Within this loess, a chernozem has formed at the surface. For practical reasons of visual representation, we designated the chernic horizon as Stratigraphic Unit 5.2 (SU5.2). In the ERT-profiles, SU1 and SU2 can be distinguished by their particularly low (less than 50 Ωm) and relatively high (300–400 Ωm) resistivity values, respectively. In contrast, SU3 to SU5 show moderate resistivities of 60–150 Ωm , thus these units cannot be differentiated from each other on the basis of their resistivity alone ([Table 1](#); Supplementary Section 3 in Supplementary Information in [S1 File](#)). The high electrical resistivities (<300 Ωm) observed at the very near surface (0–0.5 m) are not considered in the interpretation, as they are attributed to the low soil moisture at the time of measurement. Within the Black Floodplain Soil zone, SU2 to SU5 are missing beyond a sharp lateral contact with the Chernozem zone. Instead, Stratigraphic Unit 6 (SU6), a fluvial gravel of a presumed younger age than SU2, overlies the ubiquitous Upper Triassic (Keuper) mudstone of SU1. The SU6 gravels can be distinguished from those of SU2 by their higher relative elevation, higher pebble and carbonate content, different petrographies (higher share of limestone) and the sedimentary structure with intercalated sandy segments, and indications of small fining-up sequences ([Table 1](#), Suppl. Section 3 in Supplementary Information in [S1 File](#)). On top of SU6, the uppermost Stratigraphic Unit 7 (SU7) is formed by a thick humic and loamy solum, bearing evidence of both in-situ pedogenesis and the deposition as a pedosediment, i.e., overbank deposit (Suppl. Section 3 in Supplementary Information in [S1 File](#)). It is classified as a humic fluvisol and henceforth referred to as a Black Floodplain Soil. The latter is a well-know supraregional

Table 1. Characterization and interpretation of the Stratigraphic Units (SU) documented in the study area.

Strat.Unit	Core EN-RK	Thickn. [cm]	Main Sediment Characteristics	Resistivity in ERT	Interpretation	Pedo-Zone
SU1	1,32,33, 36,41, 55,58	tens of meters	unconsolidated (silty) clay; variegated colors (Munsell from 10R 5/2 and 2,5YR 4/3–6/5 BG); (vastly) non-calcareous; massive to finely-laminated and free of pebbles; clear and erosional upper boundary	low values < 60 Ω m	mudstone from the <i>Middle Keuper</i> (Weser formation)	CZ, BFZ
SU2	3,4,7,19 36-38,40, 42,51, 53,55-58	~200	gravelly, poorly-sorted fine to coarse sand; pebbles well-rounded; gravel content 10–50% (mainly quartz, chert, rhyolite and limestone); varying calcareous (1–10%); mostly reddish-brown color (between 5YR 5/2 and 5/5), clear upper boundary	high values $\leq$ 400 Ω m	<i>Weichselian</i> fluvial gravel of the 'Lower Terrace', German: "Niederterrasse"	CZ
SU3	3-10,18-31,37-45, 50-58	90-> 350	heterogeneous clayey loam; massive to finely-laminated; gravel content up to 15% (mainly quartz, rhyolite); carbonate content up to 10%; mostly reddish brown (2,5YR 3/4–5YR 6/2); clear and erosional upper boundary	low to medium values 50-150 Ω m	<i>Weichselian</i> periglacial slope debris-/deposit	CZ
SU4	3-5,7,9, 10,16,18-28, 51-54	20-90	alternate, rhythmic bedding and partial mixture of (clayey) reddish brown loam and light brown silt (7,5 YR 6/5–2,5YR 4/4), highly calcareous (5 to >10%); interfingering of SU3 and SU5.1 characteristics; gradual upper boundary	low to medium values 50-150 Ω m	<i>Weichselian</i> slope-washed loess, German: "Schwemmlöss"	CZ
SU5.1	3-10,16, 18,20-24, 26,28-31, 51,58	15-65	massive, (slightly fine-sandy to slightly loamy) silt; light (yellowish to reddish) brown (10YR 6/5–7,5YR 5/4); highly calcareous ($\geq$ 10%); contains krotovinas, earthworm channels and secondary carbonates; clear but gradual and contorted upper boundary	low to medium values 50-150 Ω m	<i>Weichselian</i> primary loess	CZ
SU5.2	3-10,15, 16,18,23,24,26, 28,29,58	45-90	mostly massive humic/mollic, dark brown solum (7,5YR 3/2–10YR 3/3); granular structure (earthworm-casts); varying carbonate contents (0–10%); occasionally incipient degradation into (luvic) phaeozem; contains krotovinas and earthworm channels; plough horizon usually with Munsell values of 4	low to medium values 50-150 Ω m	<i>Holocene</i> chernic horizon	CZ
SU6	1,2,11-14, 17,32-35, 41,46-49	100-170	gravelly sand to sandy gravel; slightly loamy, fine to coarse sandy, poorly-sorted matrix with more loamy sections; variegated but mostly reddish colors (2,5Y, 10YR, 7,5YR, 5YR to 2,5YR 6/3–5/2); calcareous (2 to >10%); well-rounded pebbles (30–60%), mainly quartz, chert and rhyolite, with higher limestone contents than SU2; sporadically with fining-up sequences; erosional lower boundary	high values $\leq$ 400 Ω m	<i>Late Weichselian</i> to <i>Early Holocene</i> fluvial gravel	BFZ
SU7	1,2,11-14, 17, 32-35, 41,46-50	70-120	massive, very humic, loamy-clayey solum/pedosediment (Munsell 7,5YR 2/1–2,5Y 3/1); clay content up to 50%; sand fraction well-sorted medium to coarse sand; carbonate content 0–10%; uppermost segments usually lighter and siltier; contains small pieces of charcoal and burnt loam; gradual lower boundary with decreasing clay- and organic carbon-, but increasing carbonate content	varied, low to medium values 50-100 Ω m	<i>Early- to Mid-Holocene</i> organic to overbank formation, poss. with weathering/ pedogenesis $\diamond$ humic fluvisol/ Black Floodpl. Soil	BFZ

The occurrence of the SU within respective sediment cores and their affiliation with the two pedogeographic zones 'Chernozem zone' (CZ) and 'Black Floodplain Soil zone' (BFZ) is indicated.

<https://doi.org/10.1371/journal.pone.0337410.t001>

phenomenon, the formation conditions of which are still controversial [74–76]. Resistivity values in the ERT profiles within this zone allow for a clear separation of SU1 (<60 Ω m), SU6 ($\leq$ 400 Ω m) and SU7 (50–100 Ω m) (Table 1; Suppl. Fig 5 in Supplementary Information in S1 File).



Fig 3. Photographic documentation of representative coring sequences. Cores EN-RK 7 and 58 refer to the Chernozem zone standard sequence; the Black Floodplain Soil (BFS) zone standard sequence is represented by core EN-RK 41. The attribution of the different deposits to stratigraphic units (SU) is

indicated. Descriptions of SU1 to SU7 can be found in Table 1 and Supplementary Section 3 in Supplementary Information in S1 File. Cores EN-RK 55 and 56 were obtained in the position of the potential mass grave. SU1 and SU2 refer to the natural Keuper mudstone and the Lower Terrace fluvial gravels, respectively. The potential backfill deposits comprise the entire sequence above the upper boundary of SU2. Blue boxes indicate the main occurrence of well-preserved skeletal remains. Note that the brownish, gravelly material at the base of RK 55 (marked with a red X) represents contamination during core extraction.

<https://doi.org/10.1371/journal.pone.0337410.g003>

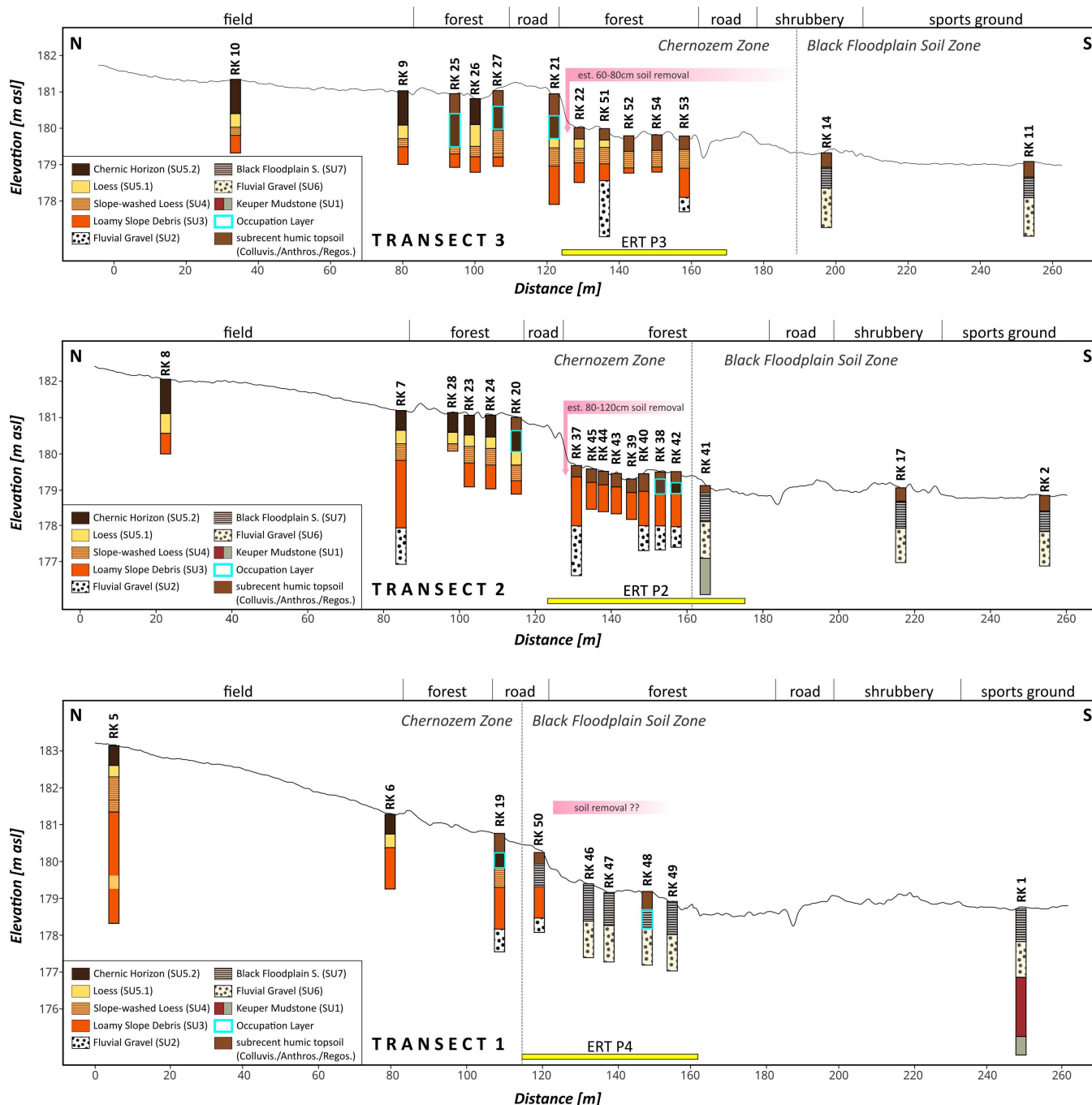


Fig 4. Simplified pedo- and lithostratigraphic sequences along the three coring transects T1 to T3. The boundary between the Chernozem and the Black Floodplain Soil zone is depicted. The estimates for truncation/soil removal in the central parts of the transects caused by ground modification during the airfield construction in 1926/27 are indicated by the pale pink rectangles. Yellow bars specify the segments covered by the respective ERT profiles.

<https://doi.org/10.1371/journal.pone.0337410.g004>

4.1.2. Transect-related stratigraphic findings. The northern parts of the coring transects T1 to T3 (cf. Fig 2), up to and including the embankment of the road “Weg zum Roten Berg”, show fairly consistent and similar stratigraphies (Fig 4). In almost every borehole in this area, stratigraphic units SU3, SU4 and SU5 are represented, although with slightly varying thicknesses. As a general trend, the slope deposits, i.e., the combined units SU3 and SU4, seem to thin out downslope. In a few positions, however, SU4 does not occur (EN-RK 6 and 8), and SU5 is occasionally obscured by occupation features (EN-RK 19, 25, 27). South of the road, the lowering and levelling of the terrain for the former airfield created a morphological step and led to a systematic truncation of the stratigraphic succession, especially in T2 and T3. The amount of intentional soil removal can cautiously be reconstructed based on the relative thickness of the lacking stratigraphic units. As for T1, the morphological step south of the road is less pronounced and it coincides with the transition from the Chernozem zone to the Black Floodplain Soil zone. At the contact of these two zones in T1, a short-distance reworking of SU3 material has apparently taken place (EN-RK 50), as this is the only position, where SU7 overlies SU3 in the whole study area. The amount of soil removal south of the road in T1 is difficult to assess. All the coring positions of Black Floodplain Soil zone that we studied so far are situated within the boundaries of the former airfield and have likely been modified by its construction. Hence, the standard thicknesses of SU7 are currently not known to us and therefore, neither is the magnitude of a possible truncation. It is not unlikely that no or only negligible soil removal occurred in this range of T1 and that the step represents a largely natural geomorphic feature here, i.e., the edge of the former floodplain. The variable degrees of soil removal across our transects T1-T3 are clearly related to the original topography prior to the airfield construction, where a convex landform with a slightly higher elevation existed (see the 180 m contour line in Fig 2B). In the center of this landform, a more extensive lowering was necessary to level the ground there compared to peripheral areas or areas outside. In the ERT profiles (Fig 5), stratigraphic units SU3-SU5 cannot be differentiated. However, the profiles clearly show the low-resistivity Keuper mudstone (SU1) at depths of 3–4 m in P2-P4, as well as the gravel of SU2 with higher resistivities and a respective thickness and depth of about 2 m. Since both aspects correspond with our coring results, it allows to infer a stratigraphic continuity of SU1 and SU2, even in segments where these units are only barely exposed through percussion coring.

The southwestern part of the AOI and of our transects is occupied by the Black Floodplain Soil zone. While in T1 circa half of the overall boreholes are located there, in T2 and T3 its boundary with the Chernozem zone lies further to the south, visible both in coring- and ERT profiles (Figs 4, 5). The very sharp contact between the two pedogeographic zones (cf. Suppl. Figs 4, 5 in Supplementary Information in S1 File) and the lack of slope deposits (SU3 to SU5) in the Black Floodplain Soil zone can only be explained by lateral fluvial erosion, eroding these sediments after their deposition. The contact of the zones therefore represents the edge of the floodplain. As lateral fluvial erosion and subsequent sedimentation of coarse material in the river bed are connected processes, it follows that the gravels of SU6 must be younger than those of SU2. Lateral fluvial activity (esp. meandering) often leads to the formation of more sandy sequences with fining-up tendencies. This can be observed in several cores in SU6 (EN-RK 12, 15 and 35) to some extent, in contrast to SU2. Across the contact of the two zones, in the ERT profiles, it is not possible to distinguish between the fine-grained topmost deposits of the Chernozem zone (SU3-SU5) and the Black Floodplain Soil zone (SU7) based on their resistivity values alone. The same is true for the two separate fluvial gravels (SU2 versus SU6). However, clear distinction is facilitated by their relative stratigraphic properties: The fine-grained deposits are much thinner in the Black Floodplain Soil zone and the gravels lie much closer to the surface compared to Chernozem zone. As these findings are well in accordance with the borehole stratigraphies, the contact between the two pedogeographic zones can be reliably mapped using ERT, even in the local absence of a high coring density. Their boundary is most pronounced in P11 (at ~45 m), well-discernible in P2 (~41 m), and has a more transitional character in P12 (~23 to 28m) (Suppl. Fig 5 in Supplementary Information in S1 File).

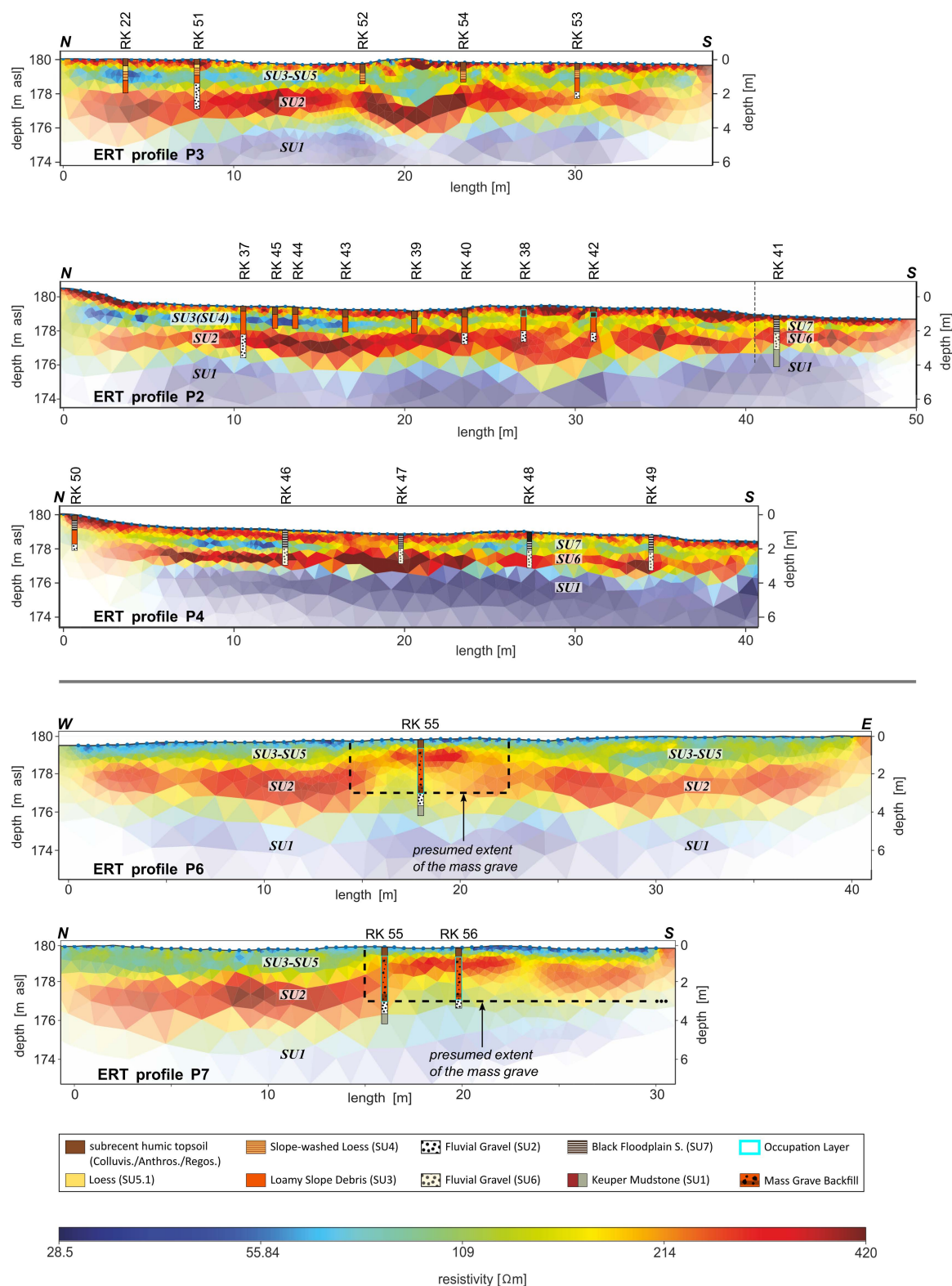


Fig 5. ERT-profiles P2 to P4, P6 and P7. The profiles P2 to P4 are aligned with the central sections of the coring transects T1 to T3; the models are based on the inversion of the Wenner configuration. Profiles P6 and P7 cross the potential mass grave in W-E and N-S directions, respectively. The

models are based on a joint inversion of a Wenner and Dipole-Dipole configuration. The vertical and horizontal extent of the potential mass grave, as interpreted from consistent results of ERT and Pürckhauer mapping, is marked with black dashed lines.

<https://doi.org/10.1371/journal.pone.0337410.g005>

4.2. Systematic localization and characterization of the potential mass grave

According to our geographic positioning of the excavation map from 1926/27 AD [45], we expected the mass grave to fall in line with transect T3 and ERT profile P3 (Fig 2). However, we did not identify a corresponding feature there, which is likely caused by substantial uncertainties in the west-east direction of the control points for georeferencing. In the following step of investigation, we turned to the corridor ca. 30 meters (± 5 –10 m) south of and parallel to the road “Weg zum Roten Berg”, as we considered this distance between the road and the mass grave discovered during the 1920s excavation reliable. Along this ~30-m line, between transects T2 and T3 (red dotted line in Fig 2C), we carried out Pürckhauer soundings every two meters and increased the resolution as necessary. The information on natural stratigraphy and the extent of soil truncation obtained from the coring transects and ERT profiles enabled us to focus on sedimentary anomalies—such as deviations in color, texture, or the presence of unusual material—that stood out from the natural deposits. The sequences of these Pürckhauer soundings mostly mirrored the percussion coring findings of the immediate surroundings: They featured loamy slope debris (SU3), overlain by slope-washed loess (SU4) in which a recent humic topsoil had formed since the truncation in the 1920s (Fig 4, position EN-RK 54). About 10 meters west of T3, however, we discovered a stratigraphic anomaly, characterized by a slightly-elevated organic matter content and the noticeable admixture of pebbles, as well as the occurrence of brick and charcoal fragments below the topsoil. As these properties are atypical for the SU3 deposits and were restricted to a very small segment of this 70-meters long Pürckhauer transect, we further explored this anomaly through percussion coring and conducted ERT measurements along two intersecting, perpendicular profiles (P6 and P7) to delineate its extent (Fig 5).

In the respective cores EN-RK 55 and 56, which are about three meters apart (Fig 5), the natural stratification is substantially disturbed down to even greater depths (approx. 280 cm) than was evidenced by the shallow (1 m) Pürckhauer soundings. All natural deposits (SU2–SU5) that occurred in this part of the Chernozem zone within the uppermost ~3 m before the 1920s ground modification are mixed in the core sequences. This leads to anomalous contents of silt, organic matter and especially gravel (Fig 3). The lower boundary of these disturbed segments is formed by the contact with the gravels of SU2, situated at ~285 cm (EN-RK 55) and ~270 cm (EN-RK 56). Since stones, pebbles, and sand with SU2-origin are dispersed across the disturbed part of the sequence, this boundary needs to be regarded as artificially lowered. Accordingly, in core EN-RK 55, the original SU2 gravels below the disturbed section have only about a third of their usual thickness (ca. 60 cm) (Fig 3), and the upper SU2 boundary is situated further downcore. For comparison, in the closest cores outside the anomaly (EN-RK 51 and 53), this boundary lies at 173 and 186 cm, respectively. Apart from allochthonous coarse-grained material, the sediment matrix contains small aggregates (<1 cm) of seemingly unaltered primary loess (SU5.1) throughout the anomalous section. As the loess has been largely removed in this part of the AOI in 1926/27 AD, its patchy occurrence in the disturbed sequences testifies to its admixture before that time. Among the unusual constituents found in the anomalous sections are also clearly anthropogenic ones: dispersed brick fragments, charcoal pieces and human skeletal remains (Suppl. Table 2 in Supplementary Information in S1 File). The latter mainly occur between 235 and 280 cm in EN-RK 55, where they also coincide with the most organic-rich deposits, and in EN-RK 56 between 170 and 190 cm coring depth (Fig 3).

In the ERT profiles, the anomaly is reflected by a thinning of the low-resistivity capping deposits and an inflated thickness of the high-resistivity segments below, likely due to the admixture of coarser material from SU2. In P6, the feature is located approximately in the middle of the profile, while it starts at around 15 m profile length in P7 (Fig 5). The lower boundary of the anomaly, however, is nearly invisible in ERT. Instead, high resistivity values of the coarse-grained deposits (>200 Ω m) slowly grade downwards into the low values (<70 Ω m) of the underlying Keuper mudstone (SU1).

The evidence above suggests that the anomalous structure is an intentional pit created before 1926/27 AD, sunken through SU5 to SU3 and the top of SU2. Within the pit, several human bones were laid down, plausibly even human bodies, because the bone fragments found are also associated with a higher organic carbon content in the deposits, which may be related to decomposed soft tissue. During the backfill process, the dug-off sediments were apparently put back in a random, unsystematic way, mixing SU2 to SU5 material. Especially the incorporation of SU2 gravels into this backfill sequence produces higher electric resistivities so that the pit stands out in ERT.

Based on the Pürckhauer prospection and the ERT results, we tentatively delimit the anomalous feature as follows (Fig 5): In W-E orientation, it has a length of ~9 meters, with core EN-RK 55 positioned right at the center. In N-S orientation, the northern margin is just one meter north of EN-RK 55, both in ERT and according to Pürckhauer prospection. Locating the southern margin was hampered by a blackthorn (*Prunus spinosa*) thicket, but the total length was confirmed to be > 15 meters.

4.3. Chronology

The pottery sherds and charcoal pieces sampled from occupation layers and archeological features during the coring campaign can provide first chronological data and might reflect the settlement period of the former village Neues (Table 2, Suppl. Section 5.1 in Supplementary Information in S1 File). For three charcoals from cores EN-RK 21, 53 and 55, calibrated radiocarbon ages ranging from the 11th to the 13th century AD were obtained. One charcoal sample

Table 2. Compilation and sampling context of different chronological information from the study area.

Core EN-...	Depth [cm]	Lab code/ Inv. No.	Layer	Pottery	¹⁴ C Bone cal AD (2σ)	¹⁴ C Charcoal cal AD (2σ)
RK 21	130	60284	occupation layer/feature	—	—	1169-1265
RK 25	119	22/220-9	occupation layer/feature	PH	—	—
RK 27	65	22/220-3	occupation layer/feature	LMA	—	—
RK 32	45	22/220-4	overbank deposit/occ. layer?	PH-MA	—	—
RK 32	85	22/220-7	overbank deposit/occ. layer?	PH	—	—
RK 35	80	22/220-10	overbank deposit/occ. layer	PH	—	—
RK 38	36	22/220-1a	colluvial deposit/occ. layer	MA/ MO	—	—
RK 38	36	22/220-1b	colluvial deposit/occ. layer	MO	—	—
RK 46	53	22/220-2	overbank deposit (BFS)	PH	—	—
RK 47	41	22/220-6	overbank deposit (BFS)	MA	—	—
RK 48	38	22/220-5a	occupation layer/feature	MA	—	—
RK 48	38	22/220-5b	occupation layer/feature	PH-MA	—	—
RK 48	55	22/220-8	occupation layer/feature	MA	—	—
RK 53	40	60282	topsoil, truncated occ. layer	—	—	1035-1160
RK 57	45	22/220-11a	topsoil/occ. layer	PH	—	—
RK 57	45	22/220-11b	topsoil/occ. layer	MO	—	—
RK 55	154	60281	feature, possible mass grave	—	—	1038-1204
RK 55	260	60280/ 22/220-13	feature, possible mass grave	—	1302-1401	—
RK 56	180	65026/ 22/220-20	feature, possible mass grave	—	1301-1398	—
RK 56	243	65027	feature, possible mass grave	—	—	4447-4337*

Abbreviations for pottery: PH=Prehistory, MA=Middle Ages, LMA=Late Middle Ages, MO=Modern era. *For this sample, the cal BC scale applies, instead of cal AD. For pottery finds and dated bones, the inventory number of the Thuringian State Office for Monument Preservation and Archeology (TLDA) is indicated in bold. For radiocarbon samples, we state the MAMS laboratory code from CEZA in Mannheim (italics).

<https://doi.org/10.1371/journal.pone.0337410.t002>

from the lower part of the anomalous feature in core EN-RK 56 at 243 cm gave an Early Neolithic age at ~4400 years BC (Table 2) and was hence excluded from the main interpretation. We consider this piece of charcoal to originate from the surface chernozem that was likely affected by well-documented Early Neolithic occupation in the immediate area [77]. Therefore, we suggest that it was mixed into the sequence during the infill of the anomalous feature and thus consider it as intrusive material. Out of the fourteen pottery sherds, seven pieces collected from cores EN-RK 27, 32, 38, 47 and 48 could be classified as (tentatively) medieval. The two bone fragments taken from the cores EN-RK 55 and 56 within the potential mass grave showed optimal overall and collagen preservation (C/N values of 3.2, collagen contents of 4.4% and 7.3%, Suppl. Table 1 in Supplementary Information in S1 File), and they returned virtually identical age ranges with 1302–1401 and 1301–1398 cal AD (2 σ) (Table 2). A higher dating accuracy was hampered by strong fluctuations of the radiocarbon calibration curve for this period [70] (Suppl. Fig 6 in Supplementary Information in S1 File).

5. Discussion

5.1. Multiphase landscape evolution of the Neuses area (Late Pleistocene–Holocene)

Although numerical age control of the sedimentary sequence is limited, relative stratigraphy and pedological evidence allow to propose a tentative model of landscape evolution in the Neuses area (Suppl. Fig 4 in Supplementary Information in S1 File). We consider this kind of reconstruction to be essential for archeological prospection, because the construction, preservation, and detectability of burial pits strongly depend on factors such as underlying stratigraphy, soil development, ground moisture, and on later modification. Therefore, by embedding the search for the Black Death mass grave into its landscape history, our prospection strategy is targeted more effectively and anomalous signals can be distinguished from natural stratigraphic variation.

1. Older terrace formation and valley incision – After deposition of the Upper Middle Terrace in the late Elsterian, on top of the Keuper remnant “Roter Berg” [48], multi-phased incision during the Saalian and Early Weichselian exposed Keuper mudstones (SU1) along the slopes, most likely during climatic transitions [78].

2. Deposition of Lower Terrace gravels – The erosional surface at the foot of “Roter Berg” was subsequently covered by Upper Pleistocene Lower Terrace gravels (SU2), generally assigned to the Weichselian Pleniglacial in Thuringia [48]. Well-dated fluvial archives in the wider region place the most intensive phases of deposition into MIS 4 and 3, again linked to climatic oscillations [79–83].

3. Periglacial slope dynamics – Thereafter, slope deposition dominated the “Roter Berg” area, forming SU3 and SU4. This is a clear indication for a destabilizing but still rather humid landscape, for which a lot of evidence exists in Central Europe from ca. 40–45 ka (later Interpleniglacial/MIS 3) onwards, when a general cooling tendency can be observed [84–86]. We consider SU3 to be a polygenetic periglacial slope debris that formed with the participation of (i) mass wasting/active layer failure, preserving the original structure of reworked SU1, (ii) solifluction that mixed weathered gravels from the Upper Middle Terrace with Keuper mudstone and early loess, creating massive and very poorly-sorted sediments, and (iii) slope-wash that generated well-sorted interbeds of loess-like deposits. These processes are widely attested in Central European mudstone landscapes during the Weichselian Pleniglacial [87–89]. SU4, laminated slope-washed loess, overlies SU3 with an erosional disconformity, implied by the accumulation of residual gravel directly at their boundary. In Central and Western European loess areas, such deposits usually reflect landscape destabilization and increasing loess input around the MIS 3/2 boundary [90–92].

4. Loess accumulation – SU4 grades upward into the massive primary loess of SU5.1, which records intensifying aeolian activity under increasingly dry and cold conditions. In Central Europe, this main loess delivery phase occurred ca. 25–17 ka, the driest interval of the Weichselian [84,90,91,93–95].

5. Renewed fluvial activity and gravel deposition – Following loess accumulation, renewed fluvial erosion extensively eroded SU2–SU5.1 in the southwest of the study area, leaving a sharp lateral contact and depositing fluvial gravel

(SU6) unconformably on SU1. SU6 is distinguished from SU2 by its higher carbonate and gravel content, higher limestone content, higher relative elevation and different sedimentary structure with indications of fining-up sequences (Fig 5; Suppl. Figs 4, 5 in [S1 File](#); Supplementary Section 3.2 in Supplementary Information in [S1 File](#)). Its stratigraphic position and character suggest correlation with latest Weichselian–Early Holocene gravels. In this youngest stage of Lower Terrace formation, river systems gradually shifted from braided to single-channel meandering in Central Europe [81–83,88,96,97].

6. Formation of soils and wetlands in the Holocene – Within SU5.1, chernozems (SU5.2) developed under relatively dry climatic conditions, sufficient carbonate supply, distinctive bioturbation, and possibly the admixture of charred organic matter from anthropogenic activity [98–102]. For Central Germany, a formation time from the Weichselian Lateglacial/Early Holocene to about 6 or 5 ka BP is assumed [98,103]. In our study area, we identified a mosaic of mostly (haplic/callic) chernozems and degradation forms towards (luvic) phaeozems, probably shaped by variable land-use intensity since the Early Neolithic (cf. [100,104,105]).

On top of SU6, a Black Floodplain Soil (SU7) was formed and/or deposited in the Gera floodplain and remains largely exposed at the surface today. Similar, thick and clayey-humic fluvisols are documented in the Rhine, Main, and Weser catchments, where they also formed on calcareous gravels of the latest Weichselian and earliest Holocene fluvial terraces during the Alleröd and Preboreal [106,107]. Elsewhere in Central Europe, Black Floodplain Soils are typically buried under thick, clastic overbank deposits [74]. They are characterized by >30 cm of a clayey and highly humic solum, formed either (i) by selective erosion of clay-humus complexes from surrounding chernozem plateaus, (ii) decomposition of in-situ organic matter, or (iii) as gyttjas under water-logging conditions. Estimated ages for their formation usually range from the Early Holocene to the Atlantic period [74–76,108,109]. For our study area, given the local topography, the loamy character of SU7, and the persistence of wetlands until the mid-19th century, overbank deposition with contributions from organic accumulation appears most likely for their formation.

5.2. Historical and archeological context of the potential mass grave

5.2.1. Successful (re)discovery of a Black Death mass grave? The anomalous subsurface feature that we detected contains human skeletal remains from different depths and segments (Suppl. Table 2, Supplementary Section 5.3 in Supplementary Information in [S1 File](#)). Two bones, one from each of the cores EN-RK 55 and 56, were subjected to radiocarbon dating (Fig 6). As the cores are about three meters apart, it can likely be ruled out, that the same specimen was accidentally sampled twice. Therefore, the nearly identical dating results (1302–1401 and 1301–1398 cal AD) (Table 2) on the two bones not only strengthen the overall chronology, but also reflect a contemporaneous burial of several individuals in the 14th century. The anomaly has the considerable horizontal extent of 9 by >15 meters and a lower boundary at ~2.8 meters in the two cores. However, since SU5 is completely missing in the surrounding cores (e.g., EN-RK 52–54) due to soil removal in 1926/27 AD, the medieval surface at this location must have been at least 0.7 meters higher than today (Fig 4). Therefore, we assume >3.5 m as the original depth of the pit. This results in >470 m³ or about 750 t of material, assuming a cuboid shape and a bulk density of 1.6 g/cm³. The findings of multiple fragments of human bones within a sizable stratigraphic anomaly are consistent with a densely-filled burial context, so that the interpretation as a mass grave seems plausible given the historical background. The geographic position of the burial and the dating of the two human bones to the 14th century – together with specific details from contemporary written sources on the timing (July 1350 to February 1351 AD), location (cemetery of Neuses) and high number of the burials (12000 bodies in 11 pits) during the Black Death outbreak in Erfurt – potentially connects the identified probable burial context to this pandemic. However, archeological, anthropological and archeogenetic verification still awaits an excavation in the near future. At the current level of investigation, other forms of interments (e.g., an ossuary) [110] and also alternative causes of mass fatalities which might have required multiple burials (such as climatic disasters, warfare, famine or other epidemic events) [32,33,111] cannot be excluded.

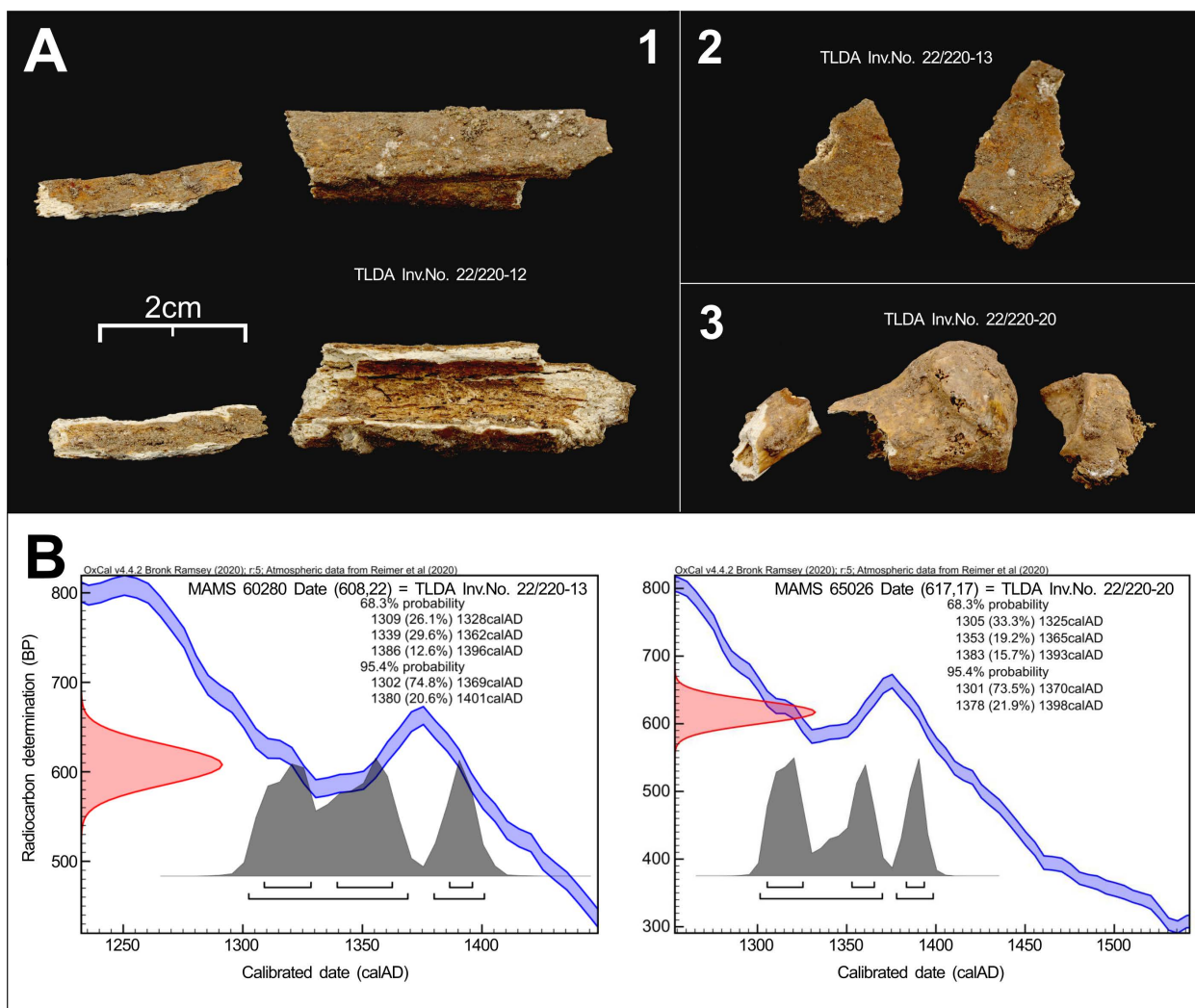


Fig 6. Documentation of human bones and their radiocarbon dates. **A1** – Fragments of a longbone from EN-RK 55 (264 cm depth, TLDA Inv.No. 22/220-12), **A2** – Fragments of cranial bones from EN-RK 55 (260 cm depth, TLDA Inv.No. 22/220-13), **A3** – Bone fragments from EN-RK 56 (180 cm depth, TLDA Inv.No. 22/220-20). **B** – Numerical dates and calibration graphs for samples TLDA Inv.No. 22/220-13 and 22/220-20, which were subjected to radiocarbon dating. Calibration was done using OXCal v.4.4.2 and the IntCal20 curve (Reimer et al, 2020).

<https://doi.org/10.1371/journal.pone.0337410.g006>

With most of the documentation and all the skeletal finds from the 1926/27 mass-grave excavation being lost, the results of our investigations (i) provide independent evidence for the presence of a dense probable burial context in a very similar position (Fig 7) and (ii) chronologically attribute the timing of the burials to the 14th century for the first time. The spatial and chronological consonance of these findings with the detailed historical accounts therefore allow the tentative assumption that this is one of the eleven Black Death pits that were previously described. Its expected dimensions are far above the average of other contemporaneous ones in Europe, so that according to our knowledge only the burial pits in Thornton Abbey (GB) compare in their extents, if not depths [21]. In Neuses, further exploration for the remaining ten specified plague pits would also allow to directly assess the validity of the written sources regarding the explicit number of those pits and buried bodies.

5.2.2. Settlement patterns, cemetery location, and mass grave placement. According to Bolle [45,54], the church of Neuses was built in the 12th century, while he places the foundation of the village slightly earlier, before 1100 AD.

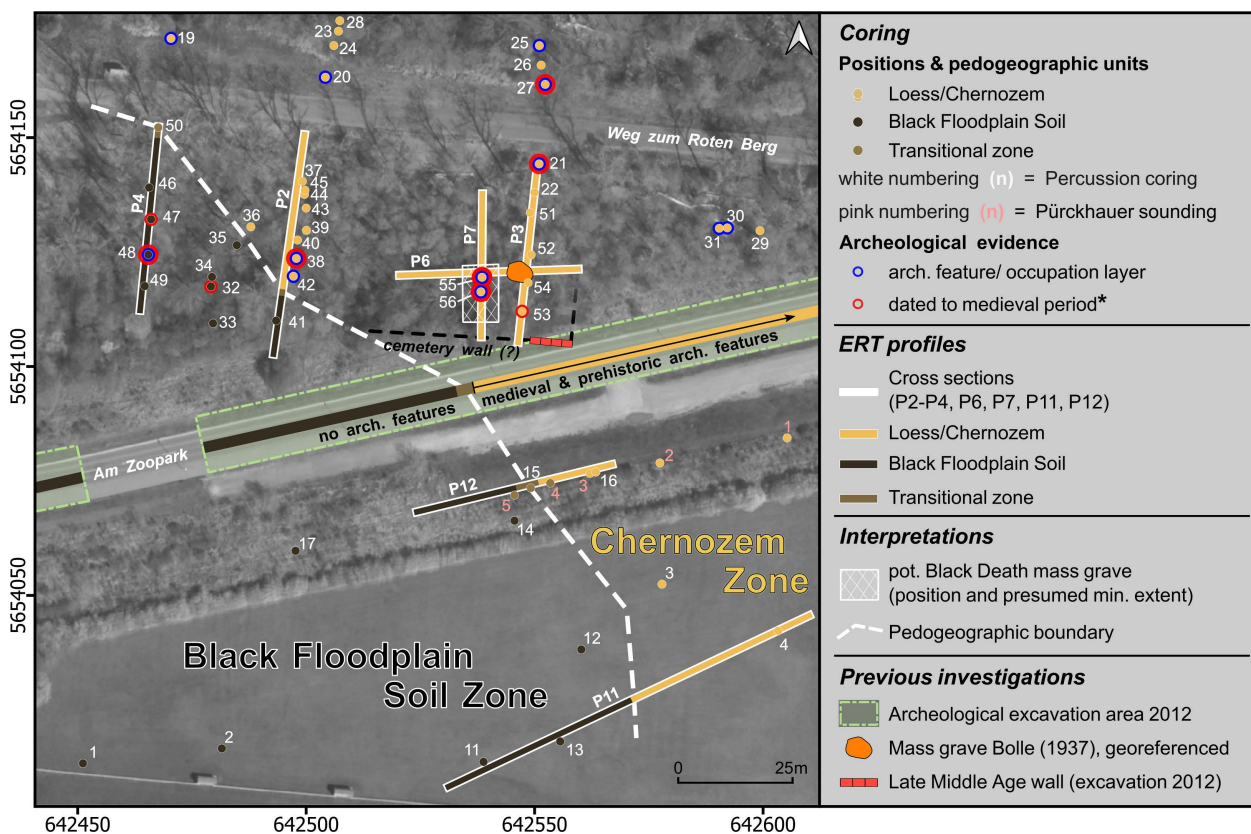


Fig 7. Synoptic illustration of the main results. ERT and coring results are integrated to infer the regionalization of the pedogeographic zones, with their boundary indicated as a white dashed line. Coring positions with presumed archeological subsurface features are marked in blue, positions with available chronological information are marked in red. Findings of previous archeological investigations are presented, as is the presumed position of the former cemetery wall (Supplementary Section 5.2 in Supplementary Information in [S1 File](#)) and extent of the potential mass grave, discovered in this study. *For details regarding the chronologies, see [Table 2](#).

<https://doi.org/10.1371/journal.pone.0337410.g007>

This is in agreement with our few ^{14}C -dated charcoals, sampled from occupation layers across the AOI, and the age determination of the pottery sherds ([Table 2](#)). While evidence for activity in the High and Late Middle Ages is present in our data, clear indication for Early Medieval activity is lacking so far. The position and spatial organization of the former village located next to the churchyard seem to be linked with the border between the two pedogeographic zones in the AOI and their extents ([Fig 7](#)). Considering the findings of the two excavations in 1926/27 and especially in 2012, all the archeological features and structures that could be related to Neuses are situated within the Chernozem zone, whereas only a few single finds have been made in the Black Floodplain Soil zone as per our definition [[45,55,56](#)]. Up until the mid-19th century, wetlands stretched in the area south of “Roter Berg”, where in places, peat was cut and stagnant water surfaces existed [[47,112](#)]. Correspondingly, it appears that Neuses was situated entirely on the higher and drier ground of the loess area with fertile chernozem soils, but on the margins of the wetter lowlands that extend in the distal River Gera floodplain. A valley edge position of the former village had already been suggested by Bolle [[45](#)] and is consistent with the findings of the 2012 excavation [[56](#)], but it can now be substantiated and clearly localized, based on our findings. The evidence suggests that the former village of Neuses was aligned both with the “Weg zum Roten Berg”, as seen for the orientation of the former cemetery wall ([Fig 7](#), Supplementary Section 5.2 in Supplementary Information in [S1 File](#)), and with the natural situation, i.e., with the margin towards the Black Floodplain Soil zone. According to our results, not only

the village itself, but also the regular cemetery and the Black Death mass graves were confined to the Chernozem zone, while the adjacent floodplain areas apparently remained unsuitable and largely unused.

The timing of the village's demise and abandonment cannot be determined easily on the basis of historical documents [45]. In 1354, Neuses was last referred to as 'villa' (approx. 'village') in written sources, while in 1516 it was described as "long-since abandoned", whereas the church was still standing until the end of the 17th century. Bolle [45] postulates that it was most likely deserted between 1354 and the middle of the 15th century. Our own chronological information on that matter is sparse, but the dates for the occupation period seem to cluster in the High to Late Middle Ages with no clear indication for activity in the 15th century and beyond (Table 2). Largely the same can be said for the preliminary age determinations during the 2012 excavation [55,56]. Bolle's assessment can therefore be broadly confirmed by the chronological data that was obtained recently, even if a more precise time frame of the event is still not established.

The choice of Neuses as a burial location for the Black Death casualties of Erfurt may also provide clues about the timing of the village's decline. In principle, consecrated ground in nearby villages would have been preferable for emergency interments, allowing at least partial adherence to Christian burial conventions [113,114]. Given the urgency of the situation and the limited workforce, however, it is striking that Neuses—located ca. 5 km from the city—was chosen instead of a more proximal site. A likely explanation is that Neuses was already in a state of decay by 1350, though not yet fully abandoned, which would have meant that the cemetery remained consecrated and available while offering sufficient unused space for mass burials. In addition, written sources reveal that Erfurt's city council held the patronage rights for the parish church of Neuses [54]. The council, advised by medical scholars, had resolved to dispose of the plague dead in specially-excavated pits [46] which apparently could only be carried out on lands directly under its authority. Taken all together, the archeological, pedogeographic, and historical evidence suggests that Neuses was selected as a burial site not by coincidence, but because its still-consecrated cemetery, political subordination to Erfurt's council, and location on dry chernozem soils provided both the authority and the practical conditions necessary for laying out large-scale plague graves. Future work, including the excavation of the potential mass grave, a detailed analysis of the 2012 excavation and continued study of the written sources, will allow to refine this hypothesis and assess how site selection related to the broader history of Neuses and its eventual desertion.

6. Conclusions

The outbreak of the Black Death in Erfurt and the supposed mass graves situated outside its city walls in the village of Neuses are unique on a European scale: Dense historical accounts, together with preliminary 20th century archeological findings, allow for a targeted and systematic prospection for a mass grave related to the second plague pandemic. Building on the existing data, our main objective was to detect a mass grave in Neuses so that material for dating and later genetic and anthropological studies could be obtained. To that end, we chose a prospection approach using electrical resistivity tomography and percussion coring. The results helped unravel the natural stratigraphic situation, which could vertically be subdivided into seven stratigraphic units, while spatially, two distinct pedogeographic areas could be identified: A Chernozem zone and a Black Floodplain Soil zone, the latter still being wetlands in medieval times. As these wetlands apparently remained unoccupied back then, this information also provided valuable insights into the positioning and internal organization of the former village and cemetery. The discovery of the potential mass grave was decisively facilitated by the obtained pedostratigraphic knowledge, which helped to better recognize slight deviation against the natural background. Two human bones from a detected potential mass grave structure were AMS radiocarbon-dated to the 14th century, reinforcing the assumption that both, the previously and recently found mass graves can indeed be related to the Black Death. Our findings also illustrate why conventional expectations about geophysical methods cannot be generalized: in Neuses, GPR failed due to the presence of fine-grained deposits, whereas ERT, in combination with sediment coring, proved decisive. This underscores the value of adapting prospection strategies to site-specific depositional conditions and embedding them in a broader geoarcheological framework. In particular, this applies to similarly challenging environments where, as in the present example, dense vegetation and strong ground modification impair the detectability

of features. To our knowledge, this study, based on close collaboration between the geosciences and the humanities may constitute the first discovery of an unmarked probable Black Death burial context, identified through systematic prospection. As a subject of research, the history of the Black Death, especially in light of the encouraging results achieved through this collaboration, once again demonstrates its fertility in advancing an interdisciplinary history of the human past.

Supporting information

S1 File. Supplementary information containing Supplementary Section 1–6.
(DOCX)

Acknowledgments

We are grateful to Susanne Lindauer, Curt-Engelhorn-Zentrum Archäometrie GmbH (CEZA) in Mannheim for carrying out radiocarbon dating, to the City of Erfurt and the Dittmar family for granting access to their properties, and to Schollenberger Kampfmittelbergung GmbH for conducting the exploration for explosive ordnance prior to our investigations. We would further like to express our thanks to Peter Jung and the geography students of Leipzig University (course 12-GGR-B-PG05, summer term of 2023) for actively supporting fieldwork and for asking all the right questions. We also thank the scientific editor Przemysław Mroczek, as well as David Colin Tanner (LIAG Hannover, Germany) and two anonymous reviewers for their helpful remarks that substantially improved the manuscript. Supported by the Open Access Publishing Fund of Leipzig University.

Author contributions

Conceptualization: Michael Hein, Nik Usmar, Johannes Rabiger-Völlmer, Johannes Schmidt, Lukas Werther, Alexander Herbig, Jan Nováček, Ulrike Werban, Martin Bauch, Christoph Zielhofer.

Data curation: Michael Hein, Johannes Rabiger-Völlmer, Marco Pohle, Birgit Schneider, Christian Tannhäuser, Jan Nováček, Ulrike Werban, Martin Bauch.

Formal analysis: Matthias Silbermann, Marco Pohle, Jan Nováček.

Funding acquisition: Ulrike Werban, Martin Bauch, Christoph Zielhofer.

Investigation: Michael Hein, Nik Usmar, Annabell Engel, Matthias Silbermann, Marco Pohle, Iris Nießen, Ulrike Werban, Martin Bauch, Christoph Zielhofer.

Methodology: Michael Hein, Annabell Engel, Matthias Silbermann, Marco Pohle, Iris Nießen, Martin Offermann, Birgit Schneider, Christian Tannhäuser, Jan Nováček, Ulrike Werban, Martin Bauch.

Visualization: Michael Hein, Johannes Rabiger-Völlmer, Matthias Silbermann, Martin Offermann.

Writing – original draft: Michael Hein, Annabell Engel, Iris Nießen, Ulrike Werban, Martin Bauch, Christoph Zielhofer.

Writing – review & editing: Nik Usmar, Johannes Rabiger-Völlmer, Johannes Schmidt, Iris Nießen, Martin Offermann, Lukas Werther, Birgit Schneider, Christian Tannhäuser, Alexander Herbig, Jan Nováček, Ulrike Werban, Martin Bauch, Christoph Zielhofer.

References

1. Aberth J. The Black Death: A New History of the Great Mortality in Europe, 1347-1500. New York (NY): Oxford University Press. 2021.
2. Benedictow OJ. The Complete History of the Black Death. Boydell & Brewer; 2020. 1200 p. Available from: <http://www.jstor.org/stable/10.2307/j.ctvxhrjg8>

3. Izdebski A, Guzowski P, Poniat R, Masci L, Palli J, Vignola C, et al. Palaeoecological data indicates land-use changes across Europe linked to spatial heterogeneity in mortality during the Black Death pandemic. *Nat Ecol Evol*. 2022;6(3):297–306. <https://doi.org/10.1038/s41559-021-01652-4> PMID: [35145268](#)
4. Ben-Ari T, Neerincx S, Gage KL, Kreppel K, Laudisoit A, Leirs H, et al. Plague and climate: scales matter. *PLoS Pathog*. 2011;7(9):e1002160. <https://doi.org/10.1371/journal.ppat.1002160> PMID: [21949648](#)
5. Bos KI, Schuenemann VJ, Golding GB, Burbano HA, Waglechner N, Coombes BK, et al. A draft genome of *Yersinia pestis* from victims of the Black Death. *Nature*. 2011;478(7370):506–10. <https://doi.org/10.1038/nature10549> PMID: [21993626](#)
6. Slavin P. The Birth of the Black Death: Biology, Climate, Environment, and the Beginnings of the Second Plague Pandemic in Early Fourteenth-Century Central Asia. *Environ Hist*. 2023;28(2):300–34. <https://doi.org/10.1086/723955>
7. Spyrou MA, Muralina L, Gnecci Ruscone GA, Kocher A, Borbone PG, Khartanovich VI, et al. The source of the Black Death in fourteenth-century central Eurasia. *Nature*. 2022;606(7915):718–24.
8. Barker H. Laying the Corpses to Rest: Grain, Embargoes, and *Yersinia pestis* in the Black Sea, 1346–48. *Speculum*. 2021;96(1):97–126. <https://doi.org/10.1086/711596>
9. Green MH. The Four Black Deaths. *Am Hist Rev*. 2020;125(5):1601–31.
10. Slavin P. From the Tian Shan to Crimea: Dynamics of Plague Spread during the Early Stages of the Black Death, 1338–46. *J Econ Soc Hist Orient*. 2023;66(5–6):513–627.
11. Schmid BV, Büntgen U, Easterday WR, Ginzler C, Walløe L, Bramanti B, et al. Climate-driven introduction of the Black Death and successive plague reintroductions into Europe. *Proc Natl Acad Sci U S A*. 2015;112(10):3020–5. <https://doi.org/10.1073/pnas.1412887112> PMID: [25713390](#)
12. Belich J. *The World the Plague Made: The Black Death and the Rise of Europe*. Princeton University Press; 2022. Available from: <http://www.jstor.org/stable/10.2307/j.ctv287skgm>
13. Ljungqvist FC, Tegel W, Krusic PJ, Seim A, Gschwind FM, Haneca K, et al. Linking European building activity with plague history. *J Archaeol Sci*. 2018;98:81–92.
14. Bos KI, Herbig A, Sahl J, Waglechner N, Fourment M, Forrest SA, et al. Eighteenth century *Yersinia pestis* genomes reveal the long-term persistence of an historical plague focus. *eLife*. 2016;5:e12994.
15. Namouchi A, Guellil M, Kersten O, Hänsch S, Ottoni C, Schmid BV, et al. Integrative approach using *Yersinia pestis* genomes to revisit the historical landscape of plague during the Medieval Period. *Proc Natl Acad Sci U S A*. 2018;115(50):E11790–7. <https://doi.org/10.1073/pnas.1812865115> PMID: [30478041](#)
16. Spyrou MA, Keller M, Tukhbatova RI, Scheib CL, Nelson EA, Andrades Valtueña A, et al. Phylogeography of the second plague pandemic revealed through analysis of historical *Yersinia pestis* genomes. *Nat Commun*. 2019;10(1):4470. <https://doi.org/10.1038/s41467-019-12154-0> PMID: [31578321](#)
17. Slavin P. Out of the West: Formation of a Permanent Plague Reservoir in South-Central Germany (1349–1356) and its Implications. *Past Present*. 2021;252(1):3–51.
18. Carmichael AG. Plague persistence in western Europe: A hypothesis. *Mediev Globe*. 2015;1(1):157–91.
19. Parker CE, Hiss AN, Spyrou MA, Neumann GU, Slavin P, Nelson EA, et al. 14th century *Yersinia pestis* genomes support emergence of *pestis secunda* within Europe. *PLoS Pathog*. 2023;19(7):e1011404. <https://doi.org/10.1371/journal.ppat.1011404> PMID: [37463152](#)
20. Bauch M, Oertel C. Late medieval plague waves in eastern Germany and Bohemia: combining narrative, administrative, epigraphic and pictorial sources with quantitative approaches. *Hist Stud Cent Eur*. 2024;4(1):30–67.
21. Willmott H, Townend P, Swales DM, Poinar H, Eaton K, Klunk J. A Black Death mass grave at Thornton Abbey: the discovery and examination of a fourteenth-century rural catastrophe. *Antiquity*. 2020;94(373):179–96. <https://doi.org/10.15184/aqy.2019.213>
22. Bauch M, Wozniak T. Mass Grave. In: *EpiMedDat* [Internet]. Available from: http://epimeddat.net/index.php?title=Mass_grave
23. Castex D, Kacki S. Bring Out Your Dead. In: *The Routledge Handbook of Archaeothanatology*. 1st ed. London: Routledge; 2022. p. 331–52. Available from: <https://www.taylorfrancis.com/books/9781351030625/chapters/10.4324/9781351030625-21>
24. Franklin ER, Mitchell PD, Robb J. The Black Death in Hereford, England: A demographic analysis of the Cathedral 14th-century plague mass graves and associated parish cemetery. *Am J Biol Anthropol*. 2023;182(3):452–66. <https://doi.org/10.1002/ajpa.24838> PMID: [37650443](#)
25. Grainger I, Hawkins D, Cowal L, Mikulski R. *The Black Death cemetery, East Smithfield, London*. London: Museum of London Archaeology Service; 2008. 63 p. (MoLAS monograph).
26. Haensch S, Bianucci R, Signoli M, Rajerison M, Schultz M, Kacki S, et al. Distinct clones of *Yersinia pestis* caused the black death. *PLoS Pathog*. 2010;6(10):e1001134. <https://doi.org/10.1371/journal.ppat.1001134> PMID: [20949072](#)
27. Kacki S, Rahalison L, Rajerison M, Ferroglio E, Bianucci R. Black Death in the rural cemetery of Saint-Laurent-de-la-Cabrerisse Aude-Languedoc, southern France, 14th century: immunological evidence. *J Archaeol Sci*. 2011;581–7.
28. Spyrou MA, Tukhbatova RI, Feldman M, Drath J, Kacki S, Beltrán de Heredia J, et al. Historical *Y. pestis* Genomes Reveal the European Black Death as the Source of Ancient and Modern Plague Pandemics. *Cell Host Microbe*. 2016;19(6):874–81. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S1931312816302086>
29. Brzobohatá H, Frolík J, Zazvonilová E. Bioarchaeology of past epidemic- and famine-related mass burials with respect to recent findings from the Czech Republic. *Interdiscip Archaeol - Nat Sci Archaeol*. 2019;X(1):79–87.

30. Haller M, Callan K, Susat J, Flux AL, Immel A, Franke A, et al. Mass burial genomics reveals outbreak of enteric paratyphoid fever in the Late Medieval trade city Lübeck. *iScience*. 2021;24(5):102419. <https://doi.org/10.1016/j.isci.2021.102419> PMID: [33997698](https://pubmed.ncbi.nlm.nih.gov/33997698/)
31. Wiechmann I, Harbeck M, Grupe G. *Yersinia pestis* DNA sequences in late medieval skeletal finds, Bavaria. *Emerg Infect Dis*. 2010;16(11):1806–7. <https://doi.org/10.3201/eid1611.100598> PMID: [21029555](https://pubmed.ncbi.nlm.nih.gov/21029555/)
32. Kahlow S. Die Pest als Interpretationsproblem mittelalterlicher und frühneuzeitlicher Massengräber. *Bull Société Suisse D'Anthropologie*. 2007;13:97–104.
33. Wright R, Hanson I, Sterenberg J. The archaeology of mass graves. *Forensic Archaeology: Advances in theory and practice*. Routledge; 2005. 256 p.
34. Lütgert S. Victims of the Great Famine and the Black Death? The Archaeology of the Mass Graves Found in the Former Graveyard of Holy Ghost Hospital, Lübeck (N. Germany), in the European Context. *Hikuin*. 2000;27:255–64.
35. Dick HC, Pringle JK, Sloane B, Carver J, Wisniewski KD, Haffenden A. Detection and characterisation of Black Death burials by multi-proxy geophysical methods. *J Archaeol Sci*. 2015;59:132–41.
36. Cannell RJS, Gustavsen L, Kristiansen M, Nau E. Delineating an Unmarked Graveyard by High-Resolution GPR and pXRF Prospection: The Medieval Church Site of Furulund in Norway. *J Comput Appl Archaeol*. 2018;1(1):1–18. <https://doi.org/10.5334/jcaa.9>
37. Conyers LB. Ground-Penetrating Radar Techniques to Discover and Map Historic Graves. *Hist Arch*. 2006;40(3):64–73. <https://doi.org/10.1007/bf03376733>
38. Witten A, Brooks R, Fenner T. The Tulsa Race Riot of 1921: A geophysical study to locate a mass grave. *Lead Edge*. 2001;20(6):655–60. <https://doi.org/10.1190/1.1439020>
39. Hunter J, Cox M. *Forensic archaeology: advances in theory and practice*. London: Routledge; 2005.
40. Abate D, Sturdy Colls C, Moyssi N, Karsili D, Faka M, Anilir A, et al. Optimizing search strategies in mass grave location through the combination of digital technologies. *Forensic Sci Int Synerg*. 2019;1:95–107. <https://doi.org/10.1016/j.fsisy.2019.05.002> PMID: [32411961](https://pubmed.ncbi.nlm.nih.gov/32411961/)
41. Chetverikov B, Babiş L, Kuzyk Z, Zayats I. Comparison of 3D Models of Mass Graves Created on the Basis of Aerial Survey Data in 1944 and 2015. In: International Conference of Young Professionals «GeoTerrace-2022» [Internet]. Lviv, Ukraine: European Association of Geoscientists & Engineers; 2022 [cited 2023 Sept 18]. p. 1–5. Available from: <https://www.earthdoc.org/content/papers/10.3997/2214-4609.2022590080>
42. Leblanc G, Kalacska M, Soffer R. Detection of single graves by airborne hyperspectral imaging. *Forensic Sci Int*. 2014;245:17–23. <https://doi.org/10.1016/j.forsciint.2014.08.020> PMID: [25447169](https://pubmed.ncbi.nlm.nih.gov/25447169/)
43. Moffat I. Locating Graves with Geophysics. In: Best practices of geoinformatic technologies for the mapping of archaeolandscape. Archaeopress Publishing Ltd; 2015. p. 45–53. (Archaeopress archaeology).
44. Pringle JK, Jervis JR, Roberts D, Dick HC, Wisniewski KD, Cassidy NJ, et al. Long-term Geophysical Monitoring of Simulated Clandestine Graves using Electrical and Ground Penetrating Radar Methods: 4–6 Years After Burial. *J Forensic Sci*. 2016;61(2):309–21. <https://doi.org/10.1111/1556-4029.13009> PMID: [27404604](https://pubmed.ncbi.nlm.nih.gov/27404604/)
45. Bolle M. Die Wüstung Neuses am Roten Berg: ein Beitrag zur Siedlungskunde mit 2 Tafeln und 2 Skizzen. *Jahrb Akad Gemeinnütziger Wiss Zu Erf NF*. 1937;53:57–85.
46. Holder-Egger O. *Monumenta Erphesfurtensia saec. XII. XIII. XIV*. Hannover; 1899. 919 p. (Monumenta Germaniae Historica. Scriptores Rerum Germanicarum in usum scholarum).
47. Lehmann E. Der bronzezeitliche Friedhof auf dem Erfurter Flughafen. *Mannus Z Für Vorgesch*. 1928;20(special issue):1–78.
48. Seidel G, editor. *Geologie von Thüringen: mit 34 Tabellen*. 2., neubearbeitete Auflage. Stuttgart: E. Schweizerbart'sche Verlagsbuchhandlung (Nägele u. Obermiller); 2003. 601 p.
49. Bushart M, Suck R. Potenzielle natürliche Vegetation Thüringens. *Schriftenr Thür Landesanst Für Umw U Geol*. 2008;78:1–139.
50. Beck HE, Zimmermann NE, McVicar TR, Vergopolan N, Berg A, Wood EF. Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Sci Data*. 2018;5(1):180214.
51. Peel MC, Finlayson BL, McMahon TA. Updated world map of the Köppen-Geiger climate classification. *Hydrol Earth Syst Sci*. 2007;11(5).
52. Eifler M. *Cronica S. Petri Erfordensis moderna*. In: The Encyclopedia of the Medieval Chronicle. Leiden - Boston; 2010. p. 421–2.
53. Bauch M, Wozniak T. Erfurt. In: EpiMedDat [Internet]. 2024. Available from: <http://epimeddat.net/index.php?title=Erfurt>
54. Bolle M. Die Kirche der Wüstung Neuseß. Ein Beitrag zur Wüstungskunde. *Mitteilungen Ver Für Gesch Altertumskunde Von Erf*. 1930;46:33–58.
55. Krauß L. Ausgrabung “Zum Zoopark” in Erfurt von Mai bis August 2012. Weimar: Thuringian State Office for Monument Preservation and Archaeology; 2012 p. 1–5. Report No.: VG-Nr.: 12/107.
56. Sczech K. Stadtarchäologischer Bericht über das Jahr 2012. *Mitteilungen Ver Für Gesch Altertumskunde Von Erf NF* 21. 2012;74:125–46.
57. Schmidt J, Voigt A, Seeburg V, Köhler A, Offermann M, Zielhofer C, et al. Georeferencing and other strategies to spatialise information from old maps – A collection of best practice recommendations [Internet]. Deutsches Archäologisches Institut, Römisch-Germanische Kommission; 2024 [cited 2024 Nov 27]. Available from: <https://repo.dainst.org/de/dataset/georeferencing-and-other-strategies-to-spatialise-information-from-old-maps>
58. Jones G. Geophysical mapping of historic cemeteries. *Tech Briefs Hist Archaeol*. 2008;3:25–38.

59. Köhler A, Werban U, Pohle M, Rabiger-Völlmer J, Schneider B, Wanger-O'Neill A, et al. Determining carbon storage of a complex peat stratigraphy using non- and minimal-invasive geophysical prospection techniques (Verlorener Bach and Loosbach valleys, southern Germany). *Geoderma*. 2024;452:117095. <https://doi.org/10.1016/j.geoderma.2024.117095>
60. Günther T, Rücker C, Spitzer K. Three-dimensional modelling and inversion of dc resistivity data incorporating topography - II. Inversion. *Geophys J Int*. 2006;166(2):506–17. <https://doi.org/10.1111/j.1365-246x.2006.03011.x>
61. Annan AP. Electromagnetic Principles of Ground Penetrating Radar. In: *Ground Penetrating Radar Theory and Applications*. Elsevier; 2009. p. 1–40. Available from: <https://linkinghub.elsevier.com/retrieve/pii/B9780444533487000016>
62. Huisman JA, Hubbard SS, Redman JD, Annan AP. Measuring Soil Water Content with Ground Penetrating Radar: A Review. *Vadose Zone J*. 2003;2(4):476–91. <https://doi.org/10.2136/vzj2003.4760>
63. Birkeland P. *Soils and geomorphology*. Oxford: Oxford University Press; 1984. 372 p.
64. Ad-hoc-AG Boden. *Bodenkundliche Kartieranleitung: mit 41 Abbildungen, 103 Tabellen und 31 Listen*. 5., verbesserte und erweiterte Auflage. Stuttgart: In Kommission: E. Schweizerbart'sche Verlagsbuchhandlung (Nägele und Obermiller); 2005. 438 p.
65. Schad P. World Reference Base for Soil Resources—Its fourth edition and its history. *J Plant Nutr Soil Sci*. 2023;186(2):151–63. <https://doi.org/10.1002/jpln.202200417>
66. Hauser S, Saito K, Pulleman M. Soil sampling (disturbed and undisturbed), handling and storage for soil chemical, biological and physical properties, v1. Standard Operating Procedure 003 [Internet]. Consultative Group for International Agricultural Research (CGIAR); 2023. 18 p. Available from: <https://hdl.handle.net/10568/134603>
67. Brown TA, Nelson DE, Vogel JS, Southon JR. Improved collagen extraction by modified Longin method. *Radiocarbon*. 1988;30(2):171–7.
68. Wood R. From revolution to convention: the past, present and future of radiocarbon dating. *J Archaeol Sci*. 2015;56:61–72.
69. Stuiver M, Polach HA. Discussion reporting of 14 C data. *Radiocarbon*. 1977;19(3):355–63.
70. Reimer PJ. Composition and consequences of the IntCal20 radiocarbon calibration curve. *Quat Res*. 2020;96:22–7. Available from: https://www.cambridge.org/core/product/identifier/S0033589420000423/type/journal_article
71. Bauer I, Endres W, Kerkhoff-Hader B, Koch R, Stephan HG, editors. *Leitfaden zur Keramikbeschreibung: (Mittelalter - Neuzeit); Terminologie - Typologie - Technologie*. 3. Aufl. München: Archäologische Staatssammlung; 2005. 198 p. (Kataloge der Archäologischen Staatssammlung München Beiheft).
72. Lütke H, Schietzel K. *Handbuch zur mittelalterlichen Keramik in Nordeuropa*. Neumünster: Wachholtz; 2001. (Schriften des archäologischen Landesmuseums).
73. Timpel W. *Mittelalterliche Keramik im westlichen Thüringen, 8.-12. Jahrhundert*. Weimar: Museum für Ur- und Frühgeschichte Thüringens; 1990. 114 p. (Weimarer Monographien zur Ur- und Frühgeschichte).
74. Rittweger H. The "Black Floodplain Soil" in the Amöneburger Becken, Germany: a lower Holocene marker horizon and indicator of an upper Atlantic to Subboreal dry period in Central Europe? *CATENA*. 2000;41(1–3):143–64.
75. Houben P. Geomorphological facies reconstruction of Late Quaternary alluvia by the application of fluvial architecture concepts. *Geomorphology*. 2007;86(1–2):94–114. <https://doi.org/10.1016/j.geomorph.2006.08.008>
76. Tinapp C, Heinrich S, Herbig C, Schneider B, Stäuble H, Miera J, et al. Holocene floodplain evolution in a central European loess landscape – geoarchaeological investigations of the lower Pleiße valley in NW Saxony. *EG Quat Sci J*. 2019;68(2):95–105.
77. Fischer AL, Hilpert J. Eine neue Verbreitungskarte der Ältesten Bandkeramik (LBK I). In: *Alles was zählt: Festschrift für Andreas Zimmermann*. Bonn: Habelt. p. 109–20.
78. Vandenberghe J. The fluvial cycle at cold–warm–cold transitions in lowland regions: A refinement of theory. *Geomorphology*. 2008;98(3–4):275–84.
79. Busschers FS, Kasse C, Van Balen RT, Vandenberghe J, Cohen KM, Weerts HJT, et al. Late Pleistocene evolution of the Rhine-Meuse system in the southern North Sea basin: imprints of climate change, sea-level oscillation and glacio-isostasy. *Quat Sci Rev*. 2007;26(25–28):3216–48.
80. Kasse C, Vandenberghe J, Van Huissteden J, Bohncke SJP, Bos JAA. Sensitivity of Weichselian fluvial systems to climate change (Nochten mine, eastern Germany). *Quat Sci Rev*. 2003;22(20):2141–56.
81. Mol J, Vandenberghe J, Kasse C. River response to variations of periglacial climate in mid-latitude Europe. *Geomorphology*. 2000;33(3–4):131–48.
82. Starkel L, Gebica P, Superson J. Last glacial–interglacial cycle in the evolution of river valleys in southern and central Poland. *Quat Sci Rev*. 2007;26(22–24):2924–36.
83. Winsemann J, Lang J, Roskosch J, Polom U, Böhner U, Brandes C. Terrace styles and timing of terrace formation in the Weser and Leine valleys, northern Germany: response of a fluvial system to climate change and glaciation. *Quat Sci Rev*. 2015;123:31–57.
84. Fischer P, Hambach U, Klasen N, Schulte P, Zeeden C, Steininger F, et al. Landscape instability at the end of MIS 3 in western Central Europe: evidence from a multi-proxy study on a Loess-Palaeosol-Sequence from the eastern Lower Rhine Embayment, Germany. *Quat Int*. 2019;502:119–36.
85. Krauß L, Zens J, Zeeden C, Schulte P, Eckmeier E, Lehmkuhl F. A multi-proxy analysis of two loess-paleosol sequences in the northern Harz foreland, Germany. *Palaeogeogr Palaeoclimatol Palaeoecol*. 2016;461:401–17.
86. Van Huissteden K, Pollard D. Oxygen isotope stage 3 fluvial and eolian successions in Europe compared with climate model results. *Quat Res*. 2003;59(2):223–33.

87. Eberle J, Eitel B, Blümel WD, Wittmann P. Deutschlands Süden - vom Erdmittelalter zur Gegenwart. Berlin, Heidelberg: Springer Berlin Heidelberg; 2017. 195 p. Available from: <http://link.springer.com/10.1007/978-3-662-54381-8>
88. Kirchner A, Karaschewski J, Schulte P, Wunderlich T, Lauer T. Latest Pleistocene and Holocene Floodplain Evolution in Central Europe—Insights from the Upper Unstrut Catchment (NW-Thuringia/Germany). *Geosciences*. 2022;12(8):310. <https://doi.org/10.3390/geosciences12080310>
89. Terhorst B. Periglacial cover beds and soils in landslide areas of SW-Germany. *CATENA*. 2007;71(3):467–76.
90. Antoine P, Rousseau DD, Moine O, Kunesch S, Hatté C, Lang A, et al. Rapid and cyclic aeolian deposition during the Last Glacial in European loess: a high-resolution record from Nussloch, Germany. *Quat Sci Rev*. 2009;28(25–26):2955–73.
91. Meszner S, Kreutzer S, Fuchs M, Faust D. Late Pleistocene landscape dynamics in Saxony, Germany: Paleoenvironmental reconstruction using loess-paleosol sequences. *Quat Int*. 2013;296:94–107.
92. Kleber A, Terhorst B, Bullmann H, Damm B, Dietze M, Döhler S, et al. Subdued mountains of Central Europe. In: *Mid-Latitude Slope Deposits (Cover Beds)*. Elsevier; 2024. p. 9–114. Available from: <https://linkinghub.elsevier.com/retrieve/pii/B9780323960038000116>
93. Lauer T, Von Suchodoletz H, Vollmann H, Meszner S, Frechen M, Tinapp C. Landscape aridification in Central Germany during the late Weichselian Pleniglacial - results from the Zauschwitz loess site in western Saxony. *Z Für Geomorphol Suppl Issues*. 2014;58(1):27–50.
94. Lehmkuhl F, Zens J, Krauß L, Schulte P, Kels H. Loess-paleosol sequences at the northern European loess belt in Germany: distribution, geomorphology and stratigraphy. *Quat Sci Rev*. 2016;153:11–30.
95. Sprafke T, Schulte P, Meyer-Heintze S, Händel M, Einwögerer T, Simon U, et al. Paleoenvironments from robust loess stratigraphy using high-resolution color and grain-size data of the last glacial Krems-Wachtberg record (NE Austria). *Quat Sci Rev*. 2020;248:106602. Available from: <https://linkinghub.elsevier.com/retrieve/pii/S0277379120305643>
96. Geßlein B, Schellmann G. Jungquartäre Flussterrassen am mittleren Lech zwischen Kinsau und Klosterlechfeld – erste Ergebnisse. *EG Quat Sci J*. 2011;60(4):400–13.
97. Schirmer W. Edifice of Fluvial Terrace Flights, Stacks and Rows. *Geosciences*. 2020;10(12):501. Available from: <https://www.mdpi.com/2076-3263/10/12/501>
98. Altermann M, Rinklebe J, Merbach I, Körschens M, Langer U, Hofmann B. Chernozem—Soil of the Year 2005. *J Plant Nutr Soil Sci*. 2005;168(6):725–40. <https://doi.org/10.1002/jpln.200521814>
99. Dreibrodth S, Hofmann R, Dal Corso M, Bork H-R, Duttmann R, Martini S, et al. Earthworms, Darwin and prehistoric agriculture-Chernozem genesis reconsidered. *Geoderma*. 2022;409:115607. <https://doi.org/10.1016/j.geoderma.2021.115607>
100. Eckmeier E, Gerlach R, Gehrt E, Schmidt MWI. Pedogenesis of Chernozems in Central Europe — A review. *Geoderma*. 2007;139(3–4):288–99.
101. Lorz C, Saile T. Anthropogenic pedogenesis of Chernozems in Germany? – A critical review. *Quat Int*. 2011;243(2):273–9.
102. Vysloužilová B, Ertlen D, Schwartz D, Šefrna L. Chernozem. From concept to classification: a review. *AUC Geogr*. 2016;51(1):85–95. <https://doi.org/10.14712/23361980.2016.8>
103. von Suchodoletz H, van Meer M, Kühn P, Wiedner K, Schunke T, Reimann T. Deciphering timing and rates of Central German Chernozem/Phaeozem formation through high resolution single-grain luminescence dating. *Sci Rep*. 2023;13(1):4769. <https://doi.org/10.1038/s41598-023-32005-9> PMID: 36959384
104. von Suchodoletz H, Tinapp C, Lauer T, Glaser B, Stäuble H, Kühn P, et al. Distribution of Chernozems and Phaeozems in Central Germany during the Neolithic Period. *Quat Int*. 2019;511:166–84.
105. Kleber M, Röner J, Chenu C, Glaser B, Knicker H, Jahn R. Prehistoric alteration of soil properties in a central German chernozemic soil: in search of pedologic indicators for prehistoric activity. *Soil Sci*. 2003;168(4):292–306.
106. Schirmer W. Valley bottoms in the late Quaternary. *Z Für Geomorphol Suppl*. 1995;100:27–51.
107. Schirmer W. Die Talentwicklung an Main und Regnitz seit dem Hochwurm. *Geol Jb*. 1983;A 71:11–43.
108. Notebaert B, Houbrechts G, Verstraeten G, Broothaerts N, Haecx J, Reyniers M, et al. Fluvial architecture of Belgian river systems in contrasting environments: implications for reconstructing the sedimentation history. *Neth J Geosci*. 2011;90(1):31–50. <https://doi.org/10.1017/s0016774600000652>
109. von Suchodoletz H, Khosravichenar A, Fütterer P, Zielhofer C, Schneider B, Sprafke T, et al. Holocene overbank sedimentation in Central Europe between natural and human drivers - The Weiße Elster River (Central Germany). *Geomorphology*. 2024;449:109067. <https://doi.org/10.1016/j.geomorph.2024.109067>
110. Kay JE, Koncz I. Archaeological Approaches to Multiple Burials and Mass Graves in Early Medieval Europe. *Mediev Archaeol*. 2023;67(1):115–36. <https://doi.org/10.1080/00766097.2023.2204667>
111. Der Schmidtstedter ET. Der Schmidtstedter Gedenkstein von 1316. Ein seltenes Kleindenkmal der spätmittelalterlichen Klima- und Kulturgeschichte Erfurts. *Mitteilungen Ver Für Gesch Altertumskunde Von Erf*. 2009;70:8–16.
112. Kirchhoff A. Die Lagenverhältnisse von Erfurt. *Mitth Ver Für Erdkd Zu HalleS*. 1895;19:1–12. Available from: <https://opendata.uni-halle.de/handle/1981185920/91444>
113. O'Sullivan D. Burial of the Christian Dead in the Later Middle Ages. In: *The Oxford Handbook of the Archaeology of Death and Burial*. Oxford University Press; 2013. p. 259–80. Available from: <https://academic.oup.com/edited-volume/38604/chapter/334707878>
114. Vivas M. Christian Burial Privation in the Middle Ages: an interdisciplinary approach (France, mid-10th–early 14th). *Edicions de la Universitat de Lleida*; 2018 p. 191–210. Available from: <http://hdl.handle.net/10459.1/65937>