CZECH UNIVERSITY OF LIFE SCIENCE PRAGUE

FACULTY OF ENVIRONMENTAL SCIENCES

Department of Environmental Geoscience

CZECH
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Crucial impact of the ancient anthropogenic settlement on soil pedogenesis

DOCTORAL THESIS

Author: Ing. Sahar Poledník Mohammadi

Supervisor: prof. RNDr. Vladislav Chrastný, Ph.D.

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Declaration

Herby I would like to inform that this thesis written by the correspond author (Sahar Poledník Mohammadi) and have not used any information without their declaration in the text. Any information made by others or literal quotations are conspicuously referenced. The thesis has not been published elsewhere.

Glossary

EDE	European Dark Earth
pXRF	portable X-ray fluorescence spectrometer
AT	Anthrosols
TC	Technosols
LE	Light elements
AH	Ant Heap

Abstract

The perception of long-term environmental modifications under natural and anthropogenic conditions is the tool of how to deal with future human sustainability. One of the most important is the variation of the climate influencing the soil cover and soil pedogenesis. Humans control not only variations in the plant species composition but also the microclimate and soil cover through feedback mechanisms.

Therefore, the reconstruction of the environmental change sequence formed under natural and anthropic conditions is essential for future predictions and sustainable development of human activity. Unfortunately, the incomplete datasets curtail the ability of archaeologists to investigate such ancient landscapes.

The research aimed to analyze the environmental impact of ancient human activities on affected land fertility by prehistoric and medieval settlements in selected sites in the Czech Republic (Pilsen, Chotěbuz) and France (Bibracte).

The Pilsen-Hradiste site has been known to archaeologists for more than 150 years. Since then, several small-scale surveys and excavations have been taken. This site had at least five phases of occupation and building activities, dating from the end of the Early Bronze Age (17th/16th century BC) to the Early Medieval Period (9th-10th century AD).

One of the best research sites of Early Middle age fortified locations in the Czech lands is undoubtedly the hillfort in Chotěbuz-Podobora near Český Těšín. This site is near the current Czech-Polish state border, where systematic archaeological research has been underway for over thirty years. It lies in the narrower north fields of the Moravian Gate, an important connecting point between the European south and north. This intensively researched site provides another excellent opportunity for studying long-term human impact on soils and the local environment in the respective periods in the easternmost part of the Czech Republic, which historically connected regions of Moravia and Little Poland.

Bibracte is a French site representing one of the best examples of significant transformations in later prehistoric Europe. This site indicates the appearance of the large enclosed settlements known as oppida. These sites, known as the beginnings of urbanism in Europe, marked the rise of proto-state communities and the focus of engagement with the expanding Roman

Empire. However, it recognized that the concept of Late La Tène (c. 250 to 30 BC) oppida as a unified group obscures a more complex picture of urban and social developments. Several unenclosed 'agglomerated' settlements represent an earlier phase of this phenomenon.

The record of environmental changes caused by anthropogenic pressure is reflected in soil morphology and properties. The occurrence of a whole sequence of fossil soils (called fossil or buried soils), or just buried soil horizons, plays a crucial role in the former environmental reconstruction and its evolution over time. Soils transformed by man to a varying extent and developed human activity results (Anthrosols and Technosols) characterized by sharp boundaries between different soil units and between individual soils. They often do not have the transition zones (pedoecotones), characteristic of natural soils properties of those developed as a result of spatially limited human activities (such as plowing, fertilization, liming, drainage, changes in the species composition of forest stands or their habitat, and activities related to production, etc.) persist at different time scales.

Some newly developed properties may become obliterated in a relatively short time (tens or hundreds of years) if the causes are eliminated (e.g., the disappearance of characteristics related to anthropogenic soil salinity). On the other hand, other soil properties permanently encoded in the "soil memory" allow us to determine the extent and intensity of the former anthropogenic pressure, even in areas where human impact on the soil is not visible during direct field observations.

Humanity's impact on natural ecosystems is well documented and has led to a decline in biodiversity globally. The anthropogenic drivers responsible for this are predominantly related to climate change and pollution that stem from the agricultural and industrial demand to support an ever-growing population.

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1. Introduction

Sedimentary archives implement a record of the human environment interaction during the Quaternary. The geochemical composition of soils and sediments can be affected by ancient human occupation; therefore, this methodological approach on soils becomes necessary for archaeological investigations (Holliday, 2004; Ackermann et al., 2015). Ancient settlement activities, specifically the deposition of biomass, ashes, and organic matter can substantially increase the concentrations of nutrients (P, K, S, Zn, and Cu) in the topsoil layer covering the archaeological sites. Such an impact can change the soil's mental composition caused by settlement activities. Ancient settlement activities can increase the concentrations of nutrients in the soil to the same level as recent intensive fertilizer applications on an adjacent arable field used for vegetable production (Šmejda et al., 2017).

The variety of environments and cultural contexts can improve our knowledge about the characteristics of human activity. Documenting long-term environmental changes under natural and anthropic forces helps facilitate sustainable development (Mercuri and Florenzano, 2019). A further valuable proxy to determine the human impact on a landscape via the interpretation of human-induced fire is charcoal (produced by the incomplete burning of wood) (Miao et al., 2019). Microcharcoal from fossil records can provide an opportunity to explore past climate change and human activity (Jaffé et al., 2013). Human activities profoundly impact the environment at low altitudes and high geographical latitudes. The palynological studies also detected human influence on vegetation since the mid-late Holocene (Kramer et al., 2010).

Archaeological site locations are an essential data set for investigating the cultural and social landscape's long-term and large-scale transformations. Wilkinson (2003) argued that as social processes change, they materialize different 'signature landscapes' the comparison of which can reveal the dynamics of past human societies. Past settlement landscapes associated with early cities and polities are particularly extensive. Investigating these landscapes requires data from across large areas. But locating ancient cultural heritage sites through the archaeological survey is expensive in terms of time and resources. Surveys could be the best employed in concern with other spatial research methods, which can be used to build up datasets that allow research over long periods and extensive areas (Menze and Sherratt, 2006; Liu et al., 2013).

Historical maps are one of such data sets that offer information from a range of periods that remote sensing-based approaches can complete to identifying cultural heritage sites (Casana, 2009; Petrie et al., 2019). Historical maps have the potential to complement other spatial research techniques, such as remote-sensing, thereby facilitating holistic investigations of archaeological landscapes (Rondelli et al., 2013).

Geographical information systems (GIS)-based methods are essential to transforming old and sometimes forgotten documents into spatial data for multi-method analysis, including sources that are difficult to compare as discrete documents (Wheatley and Gillings, 2002). GIS allows maps, plans, and other features to transform into digital vector data with spatial coordinates, points, lines, and polygons that can store additional attribute values along with x, y, and z coordinates. Many GIS tools are open source and open access. They can be combined with other accessible data sources such as Google Earth Imagery, dramatically improving cultural heritage landscape data resolution in many parts of the world (Smith and Chambrade, 2018). Weathering products may differ, depending on the climate at weathering or exposure of the rock (Chesworth et al., 2004).

The rates of weathering, alteration, soil accumulation, and evolution govern by climates like temperature, the availability of H_2O, and biotic factors (Birkeland, 1999). The amount of precipitation is crucial, due to the leaching process to transfer silica, clay, and carbonates from the top of soils too deep by water, which change soil development (Graham and O’Geen, 2010).

2. Aims of the thesis

The main aim of this project is:

1) to assess the ecological impact of human activity on soils present at archeological sites,

2) understand long-term environmental changes induced by anthropogenic impact in such environments. For the initial, we have the following objectives:

- To understand that archaeological features resulting from ancient human activity (pits, walls, and ditches filled by sediments and soils) may enhance water and nutrient availability for plants growing over such features.
- To describe the multi-dimensional activities in settlements, their development, and change to rate accumulation of phosphate and other chemical indicators of human impact over time.
- Quantification and monitoring crops phenological cycle, nutrient cycling, and soil evolution.

3. Literature review

The literature review is divided into four chapters to distinguish the different parts of anthropogenic soils studies. The first chapter defines anthropogenic activities and implication of it on soils, sedimentary archives, and ancient settlements as an essential source of nutrients in research. The second chapter outlines the human Impact on All Soil-Forming Factors. Soils are formed through the interaction of five major factors: time, climate, parent material, topography and relief, and organisms. The relative influence of each factor varies from place to place. Still, the combination of all five factors normally determines the kind of soil developing in any given site. Still, the research on anthropogenic soils does not obey any of the regular scientific disciplines. The third chapter partially describes historical maps as a complement of spatial research techniques, such as remote-sensing and Geographical information systems (GIS). The last chapter describes soils with strong human influence, their managements, and the way to analyze these soils containing X-ray flourescence, micromorphology, magnetic sustabilty principles of pXRF. The chapter also includes a critique of the use of these devices. These devices create specific closed data called compositional data. The last chapter of the literature review describes what compositional data are and how to work, optically simulated dating (OSL), and dataset characteristics.

As the spatial relics of human activities, settlement sites carry and record information about human adaptation and transformation of the environment; interpreting and revealing the environmental information of settlement distribution can provide conditions for further understanding the interaction between humans and the environment during this period. Therefore, by studying the changing patterns of the distribution of human prehistoric sites and their geographical background, we can understand the adaptation and transformation processes of prehistoric humans to the living environment (Pachauri and Meyer, 2014; Putzer et al., 2016), which are an important topic in environmental archaeology research. Attempts to explain the relationships among prehistoric human settlement information, the development of early civilizations, and the natural environment date back to the 1950s (Chang, 1968). These explanations allow us to use the past to further our understanding of the dynamic and complex systems in which humans interact with nature. Discussing the relationship between the spatial and temporal distribution of settlements and the geographic environment around the changing patterns of human prehistoric sites and their geographic context (Putzer, 2016; Dutt et al., 2019) is an essential environmental, archaeological study issue.

3.1. The implication of anthropogenic activities on soil

The implications of anthropogenic activities on soil have been discussed extensively for many years in numerous publications. For example, Dazzi and Lo Papa (2015) defined seven major types of anthropogenic soils, all induced by human activities: (1) soils that were altered because of land use changes, for example, Solonchaks developed from Cambisols in arid environments because of irrigation; (2) diagnostic soil horizons related mainly to long-term applications of organic matter or to wetland cultivation; (3) new parent material, which is a mixture of gathered mineral and/or organic materials resulting from landfills and other forms of accumulated waste originating from human activities; (4) profound soil disturbance, including deep plowing, trenches, excavations, pipelines, and construction sites without any distinguishable horizons; (5) landform changes, referring to rearrangement of the land topography mainly applied to improve agricultural practices (the most obvious example being terracing); (6) topsoil changes, which refer to the combined impact of process like land use change (tillage, deforestation), change in soil pH (liming), regulation of soil water content (irrigation and drainage), addition of nutrients (fertilization), and/or contamination; and (7) soil construction/reconstruction: soils that are produced for the need/ opportunity to "reconstitute" and/or generate new soil, mainly for areas degraded by natural disaster or termination of industrial or military activities; another option is tailoring of soil properties for specific crop growing. In all of these, the parent material is of minor importance, and human impact plays a significant role. Here, we provide five examples demonstrating some of the leading consequences of human impacts on the different soil-forming factors in the context of environmental implications. It is essentially impossible to quantify anthropogenic impacts on soil formation, mostly because of the complexity and the numerous direct and indirect processes involved. However, below, we offer several examples demonstrating the global scale of anthropogenic factors and how the magnitude of human impacts are as large as, sometimes even more significant than, that of natural processes. It is noted that these consequences are often the outcome of a combination of anthropogenic effects.

One fast and dramatic process induced by human activity is soil erosion. The accelerated loss of topsoil is so rapid and so extensive that a recent report by the Food and Agricultural Organization of the United Nations (FAO, 2008; FAO and ITPS, 2015) suggests that soil erosion should be considered as mining of a nonrenewable natural resource. The report also indicates that the erosion rates of arable or intensively grazed lands are orders of magnitude faster than natural erosion rates. That soil on hilly slopes will ultimately be exhausted under standard agricultural practice. Wuepper et al. (2020) demonstrated that agricultural practice has a major human impact. They found significant differences in soil erosion rates between countries with joint borders despite their natural erosion rates being practically indistinguishable. Thus, for example, Wuepper et al. (2020) found a striking gap between Haiti, with soil erosion rates of >75 t ha^{-1} year^{-1}.

3.2. Sedimentary archive

Sedimentary archives implement a record of the human environment interaction during the Quaternary. The geochemical composition of soils and sediments can be affected by ancient human occupation; therefore, this methodological approach on soils becomes necessary for archaeological investigations (Holliday, 2004; Ackermann et al., 2015). Ancient settlement activities, more specifically the deposition of biomass, ashes, and organic wastes, can substantially increase the concentrations of nutrients (P, K, S, Zn, and Cu) in the contemporary topsoil layer covering the archaeological sites. Such an impact can change the soil's mental composition caused by settlement activities. Ancient settlement activities can increase the concentrations of nutrients in contemporary soil to the same level as recent intensive fertilizer applications on an adjacent arable field used for vegetable production (Šmejda et al., 2017).

In various environments and cultural contexts, multiple studies can improve our knowledge about the characteristics of human activity. Documenting long-term environmental changes under natural and anthropic forces helps facilitate sustainable development, where understanding human impacts on shaping the landscapes in the present and past will be crucial (Mercuri and Florenzano, 2019). A further valuable proxy to determine the human impact on a landscape via the interpretation of human-induced fire is charcoal, which is produced by the incomplete burning of wood (Miao et al., 2019). Microcharcoal from fossil records can provide an opportunity to explore past climate change and human activity (Jaffé et al., 2013). Human activities profoundly impact the environment, not only at low altitudes but also at high geographical altitudes. The palynological studies also detected human influence on vegetation since the mid-late Holocene (Kramer et al., 2010).

Archaeological site locations are an essential data set for investigating the cultural and social landscape's long-term and large-scale transformations. Wilkinson (2003) argued that as social processes change, they materialize different ‘signature landscapes’ the comparison of which can reveal the dynamics of past human societies. Past settlement landscapes associated with early cities and polities are particularly extensive. Investigating these landscapes requires data from across large areas. But locating ancient cultural heritage sites through the archaeological survey is expensive in terms of time and resources. Surveys could be the best employed with other spatial research methods, which can be used to build up datasets that allow research over long periods and extensive areas (Menze and Sherratt, 2006; Liu et al., 2013). Historical maps are one of such data sets that offer information from a range of periods that remote sensing-based approaches can complete to identifying cultural heritage sites (Casana, 2009; Petrie et al., 2019).

3.3. Ancient settlement activities as essential sources of nutrients

Human activities cause long-term changes in the chemical properties of soil. Chemical analysis of archaeological soils may lead to identifying areas affected by various human activities in the past (Dupouey et al., 2002; Salisbury, 2013; Charzyński et al., 2015). Despite the increasing interest in the multi-element analysis of archaeological soils (Terry et al., 2004; Fleisher and Sulas, 2015), the determination of phosphorus (P) remains the most important issue in many cases. The archaeological significance of other elements has been studied in various geographical and cultural contexts (Middleton and Price, 1996; Middleton, 2004; Wilson et al., 2008; Oonk et al., 2009a). Phosphorus cycles on a geological timescale and many human activities such as organic waste, bones, biomass ashes and feces deposition are connected with an accumulation of P (Arrhenius, 1931; Terry et al., 2004; Holliday and Gartner, 2007). Other elements that indicate past settlement activities are calcium (Ca) and magnesium (Mg). Accumulation of Ca and Mg on archaeological sites is linked to the use of Ca and Mg-rich clay sediments for the construction of buildings (Hejcman et al., 2013a), deposition of mortar from the destruction of buildings (Closset-Kopp and

Decocq, 2015), and to the deposit of biomass ashes and bones (Hejcman et al., 2011; Salisbury, 2013).

A disadvantage of Ca and Mg for archaeological prospection is their susceptibility to leaching and changing their concentration within the soil profile after deposition, particularly in areas with high precipitation (Hejcman et al., 2013b). In addition, analyzing Ca and Mg concentrations to identify human activities is difficult on substrates naturally rich in Ca and Mg. The fourth essential element is potassium (K), which accumulates in archaeological sites mainly because of the use of K-rich clay sediments for constructing buildings and depositing biomass ashes and feces (Hejcman et al., 2011; Hejcman et al., 2013a). K is also highly susceptible to leaching in the ion form, much more than P. Therefore, it is considered a less reliable indicator of human activities than P. The fifth and sixth elements are zinc (Zn) and copper (Cu). Both are microelements present in plant and animal biomass; therefore, they accumulate due to the deposition of organic materials such as faeces, cadavers, plant biomass, and biomass ashes (Hejcman et al., 2011). Zn is susceptible to leaching in acid soils, but Zn losses are minimal in Ca-rich soils with alkaline soil reactions. Extraordinarily high concentrations of elements in soils and sediments can indicate mining and metallurgical activities of nonferrous metals (Ash et al., 2014; Horák and Hejcman, 2016; Knabb et al., 2016). The seventh element that may indicate human activity is sulfur (S). It is an element which has thus far received very little attention from archaeologists. The accumulation of S is connected with the deposition and decomposition of organic materials. In plants and animals, S is found in the amino acids cysteine and methionine, and therefore in proteins, in many cofactors and prosthetic groups, peptides such as glutathione, in sulfolipids, sulphated polysaccharides, and many secondary metabolites such as glucosinolates and alliins (Kopřiva, 2015). Sulfur cycling in ecosystems is much quicker than the cycling of P, therefore, the S enrichment of archaeological soils does not remain as high over a long period as the P enrichment. We will use this knowledge of the differential cycling rates of S and P in the soil as a proxy for the differentiation between the recent deposition of organic P and its ancient deposition. Local conditions and circumstances can limit the applicability of some elements as potential indicators of human activity; for example, Vyncke et al. (2011) disregard copper due to the very low variance of its detected concentrations. In the past, different extraction methods and instruments were used to identify concentrations of the above-mentioned elements in archaeological soils. To investigate archaeological sites efficiently, we need a cheap method which can be used directly in the field to identify concentrations of a broad range of elements and to aid the delimitation of different activity areas during the survey or excavation processes. A portable XRF spectrometer, which enables the determination of a broad spectrum of elements, can be used for this task. Having used this equipment for an archaeological landscape survey, we estimate that approximately 100 measurements localized by GPS can be routinely performed daily directly in the field (depending mainly on the difficulty of the terrain and climate).

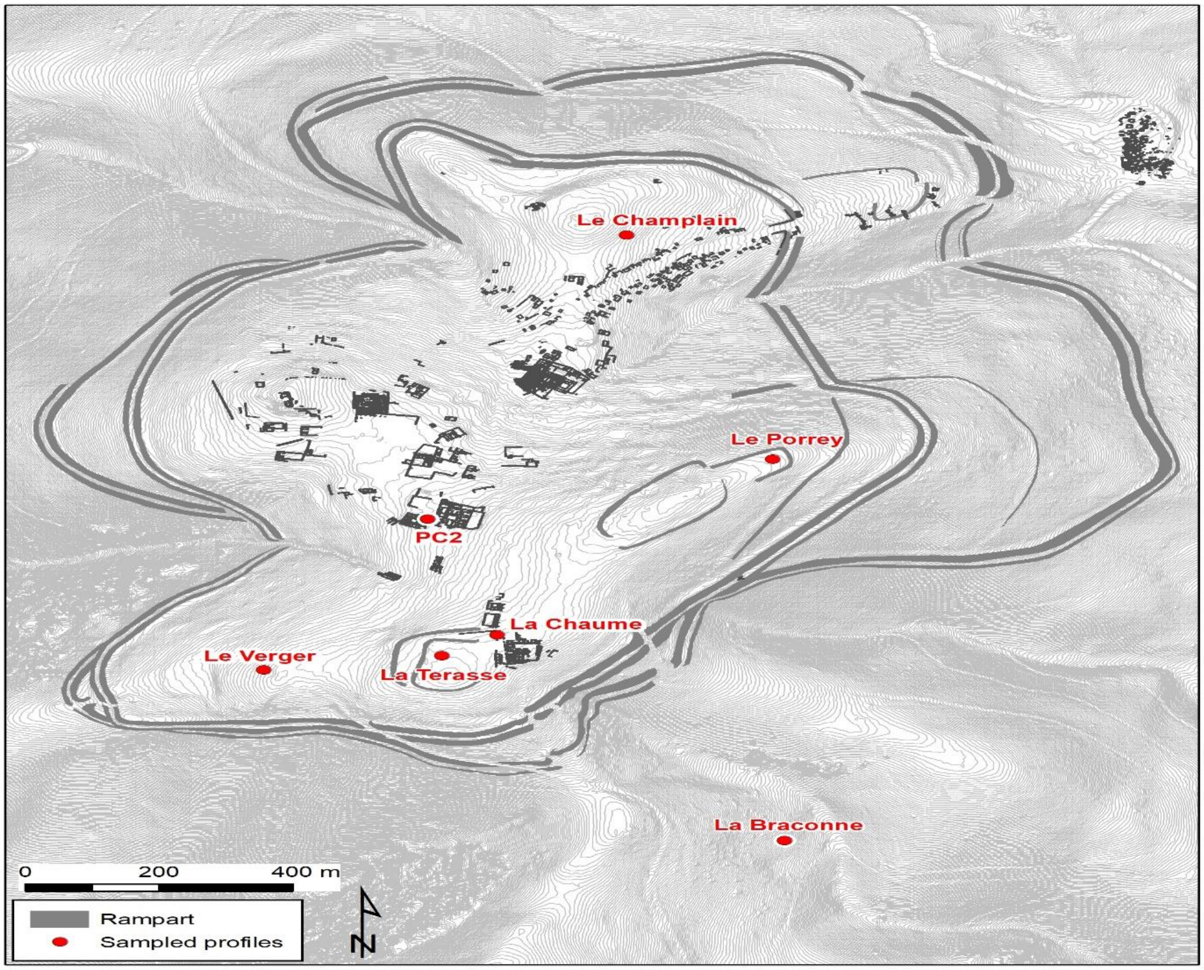

Figure. 1. Topographical map of oppidum Bibracte with the location of the sites which provided data for PCA analyses; La Champlain, Le Porrey, La Braconne, La Chaume, La Terrasse, Le Verger, Parc aux Chevaux (PC2).

3.4. The Human Impact on All Soil-Forming Factors

Throughout the development of soil science, many definitions of “soil” have been suggested. However, in all cases, it has always been clear that the sustainability and prosperity of life depend on the quality of soils. The developed five soil-forming factors (Jenny, 1941; 1961) accepted by the soil science community are (i) parent material, (ii) time, (iii) climate, (iv) topography and relief, and (v) organisms. Soil formation is usually considered to be a long-term process. It is noted that these factors are not independent but rather show complex and high-order interactions that vary over time. Almost a century after the first formal definition of the soil forming factors, Yaalon and Yaron (1966) argued that human induced changes in soil-forming processes should be considered as an integral, independent factor. This should be included as another (sixth) recognized forming factor, called meta pedogenesis, which results from anthropogenic activity on soil. Richter and Yaalon (2012) and recently Richter (2020) refer to this factor as anthropogenesis, elegantly explaining the concept and reviewing the literature related to its development. Anthropogenic effects and their impact on the soil modification rate were subsequently recognized as an independent factor (Dudal, 2005; Richter and Yaalon, 2012).

Here, we follow Yaalon and Yaron (1966) and their definition of meta pedogenesis by proposing that, because anthropogenic effects have become so significant and so influential, they are often not only an additional factor or “disturbing agent” but also actually profoundly affect each of the five original soil forming factors. We note that here we examine processes that are active currently. We do not claim that anthropogenic activities have changed the total soil inventory, nor that all global soils formed over eons are profoundly affected by human activities. To justify this argument, we briefly discuss each of the original soil-forming factors and include examples of how humans are domesticating and disrupting soils and how anthropogenic effects have become the most dominant influences on each of them.

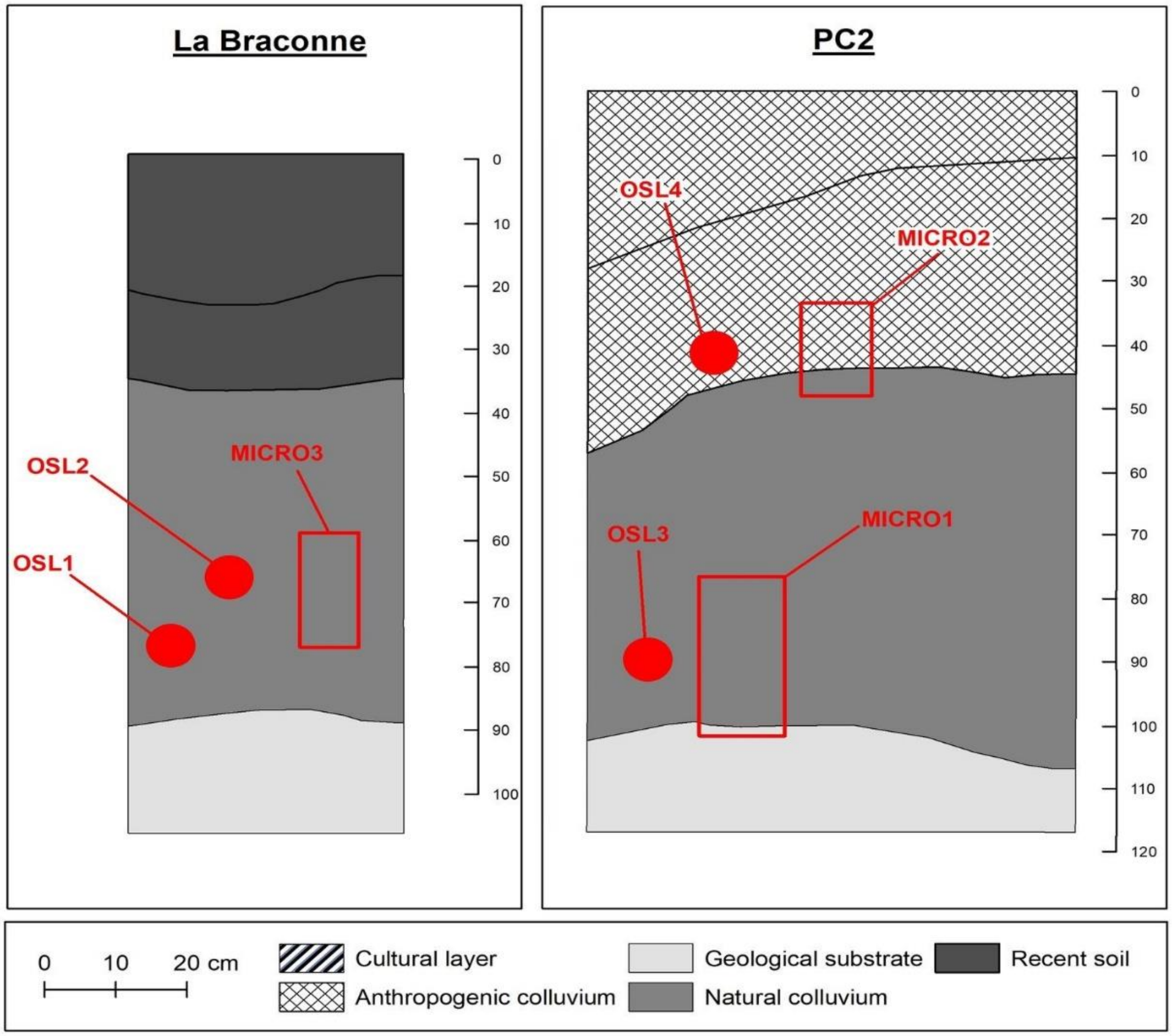

Figure. 2. General observed categories at La Braconne (BRAC) and Parc aux Chevaux (PC) with sampling positions. **La Braconne (BRAC)**: Recent soil with a clast of approx. 5 cm and roots with organic matter (Depth: 0–30 cm), Natural colluvium with the clast 5 cm (Depth: 30-85 cm), and Geological substrate (>80 cm). Samples positon of 1 and 2 for optically stimulated luminescence dating, and 3 for micromorphological studies. **Parc aux Chevaux (PC)**: anthropogenic colluvium with clast of approximately 10 cm (Depth: 0–20 cm), anthropogenic colluvium with clast about 5 cm (Depth: 20–40 cm), Natural colluvium with the clast 5 cm (Depth: 40–80 cm), and geological substrate (>80 cm). Samples for OSL are marked by red circle, while position of micromorphological samples is marked by red squares.

3.4.1. The five soil- forming factors

3.4.1.1. Parent Material

In the past, the soil composition was derived from its parent geological material. Parent material is a combination of bedrock weathered in place and geologic material transported by wind, water, ice, and gravity, supplying together the mineral components of the soil. However, more recently, massive anthropogenic activity has strongly influenced soil composition, added new anthropogenic sources, and changed the design of many current natural sources. The (dry basis) mass of human-made materials that are comparable to the soil parent material, including concrete, aggregates (mostly gravel and sand), and bricks, was reported (Elhacham, 2020) recently to reach around 90% of the global biomass, thus emphasizing the staggering extent of anthropogenic materials being added to the pool of potential soil components. Moreover, many transport processes that are described hereafter (e.g., dams that change river transport and wind dust composition) are influenced strongly by human activities. New transport processes that diversify soil composition, like mixing different horizons with advanced machinery and moving large amounts of soil, have become common practices (Conry, 1972; Herrmann, 2018). Another significant effect on soil composition is the introduction of soil amendments that have become common in recent decades. Such amendments include composting, fertilizing, liming, and deposition of treated sewage sludge. The large impact of anthropogenic activity, in general, and soil amendments, in particular, on the soil composition should be considered, keeping in mind that (i) the total amount of cropland grew dramatically by more than 300% between 1820 and 2015, and (ii) the share of land used for agriculture is above 30% of the total land area in most parts of the world (Ritchie and Roser, 2013). It is further noted that many indirect and complex interactions, originating from processes related to the other forming factors, strongly influence parent material. For example, enhanced biological activity through agricultural practices can enhance weathering of the parent material. In addition, pollution processes such as acid rain and (anthropogenically generated) dust deposition (for example, from fly ash following the burning of fossil fuels) can deplete or substantially enrich the soil mineral metrics derived from the parent material. A recent example of lead (Pb) contamination in urban soil (Wade et al., 2021) in North Carolina, USA, demonstrated how Pb originating from human-made leaded gasoline and paints altered the upper soil layers. Lead concentrations high above geogenic background levels were detected in the upper

50 cm of the soil, demonstrating anthropogenic Pb enrichment. In fact, both the IUSS Working Group WRB (2014) and the USDA and Soil Survey Staff (2010) acknowledge anthropogenic soils (often-termed anthrosols, anthroposols, antropozem, or anthropic soils (Dazzi and Papa, 2015) and offer some classification for them, as detailed further in the Environmental Implications and Extent of Human Influence section below.

3.4.1.2. Time

Human activity is altering the time scale of soil formation. It has been argued that the anthropogenic factor is orders of magnitude faster than the "natural" processes that affect soil formation (hundreds of years vs. hundreds of thousands and even millions of years, respectively (Dror et al., 2017). It is noted that there are also several fast, natural processes, like landslides or flood events; although many of them are attributed to climate change, they also involve anthropogenic factors. In general, anthropogenic processes are on the order of hours (e.g., pollution accidents) to days (e.g., deep plowing, liming, and fertilizing) to years (e.g., terracing, landfill operation, or land use change). Soil is the ultimate sink for most of the substances, which are added to the upper soil layers at high rates and change the composition of the matrix and its properties. In all cases, when considering the change compared to the soil formation rate, it is clear that human activity is impacting soil composition and structure at a much higher rate than the natural process. Moreover, Pimentel et al. (1995) showed that anthropogenic soil erosion proceeds rapidly, significantly faster than soil formation rates; these authors indicated that "nearly one-third of the world's arable land has been lost" over 40 years. In a later study, Pimentel (2006) estimated that soil loss from the land area is 10−40 times faster than the soil renewal rate. Similar rates of soil erosion were reported by Montgomery (2007), who found that erosion in conventionally plowed agricultural fields are orders of magnitude faster than soil formation rates.

3.4.1.3. Climate

Anthropogenic factors that lead to climate change are already well recognized, and current discussions are centered on a better understanding and quantifying of the multifactorial processes of anthropogenic activity that lead to climate change. The numerous publications, reports, and databases that link climate change to human activity touch on every aspect of this "soil-forming factor". It is well established that human activity influences factors like surface temperature (EPA, 2021) and precipitation distribution and amount, frequency, and amplitude of extreme climate events (e.g., hurricanes, floods, droughts). Dry land is projected to cover half of the global land surface by the end of the 1st century due to climate change that led to its fast expansion (Huang et al., 2016). Glacial melting that exposes land covered by ice and sea level rise that will cause land loss are also reported frequently (Nicholls and Cazenave, 2010).

The global impact of anthropogenic climate change on soil can be demonstrated by considering (i) the rate of soil erosion and (ii) the loss of soil organic carbon (SOC) (Borrelli et al., 2020).

3.4.1.4. Topography and Relief

Human activity changes topography on large scales. For example, dams on rivers, road construction, and urbanization processes often alter topography. Grill et al. (2015), reported that 48% of all river volume has already been moderately to severely impacted by either flow regulation, fragmentation, or both, with this number increasing to 93% upon completion of all dams under construction or in planning at the time of writing the article. Another example of large-scale modification is the loss of sediments once transported through the Nile River and deposited on the flood plain and Egyptian delta. Today, more than 98% of the sediment is deposited at Lake Nasser,45 which has resulted in the loss of silt rich in silica, aluminum, iron, and other trace elements and low in nitrogen in the Egyptian delta. This loss has led to modifying the soil composition in the delta and, in turn, to the intensified application of synthetic fertilizers (Fairbridge et al., 2012). Engineered drainage control of large basins to reduce flooding risks and designed planting and vegetation growth are also greatly influencing topography. For example, Jaramillo and Destouni (2015) reported that 46 and 50% of the land areas in 100 major basins around the world, which cover 35% of the Earth's land area, have been moderately and strongly, respectively, Desertification processes, too, are impacted strongly by human activity. Anthropogenic terrestrial sediment deposits often termed "legacy" or anthropogenic sediments, have been discussed often in the literature and present a broader view of this human impact. James (2013) presents several definitions of legacy sediments; the most general definition includes multiple human activities that lead to various sedimentary structures and textures (primarily alluvium or colluvium), processes, and depositional sites. In this definition, James (2013) includes a wide spectrum of anthropogenic activities, including agricultural practices, land use changes like deforestation, milling, mining, logging, and damming or rerouting rivers and water ways. James (2013) also offers multiple examples from human history (from Roman times in Europe to European settlement in Australia and North America). He suggests that these legacy sediments could cover entire floodplains with a thick "young soil" layer. Terraces are another example of anthropogenic engineering of surface topography, with a history dating back 5000 years. Terraces are ubiquitous in hill slopes and mountains and can be found in many parts of the world, including Asia, Europe, the Middle East, North and South America, and Africa (Wei et al., 2016). Terraces often substantially modify the hydrology and biochemical cycles in and around their location (Moser et al., 2009). They reduce natural soil erosion and runoff and allow biomass accumulation and nutrient enrichment. Because of their global spread and their impact on large areas, they are a good example of the strong anthropogenic impact on regional topography. Another significant impact on the land topography is related to infrastructure facilities such as transportation (roads, rail tracks, parking lots) and mines.

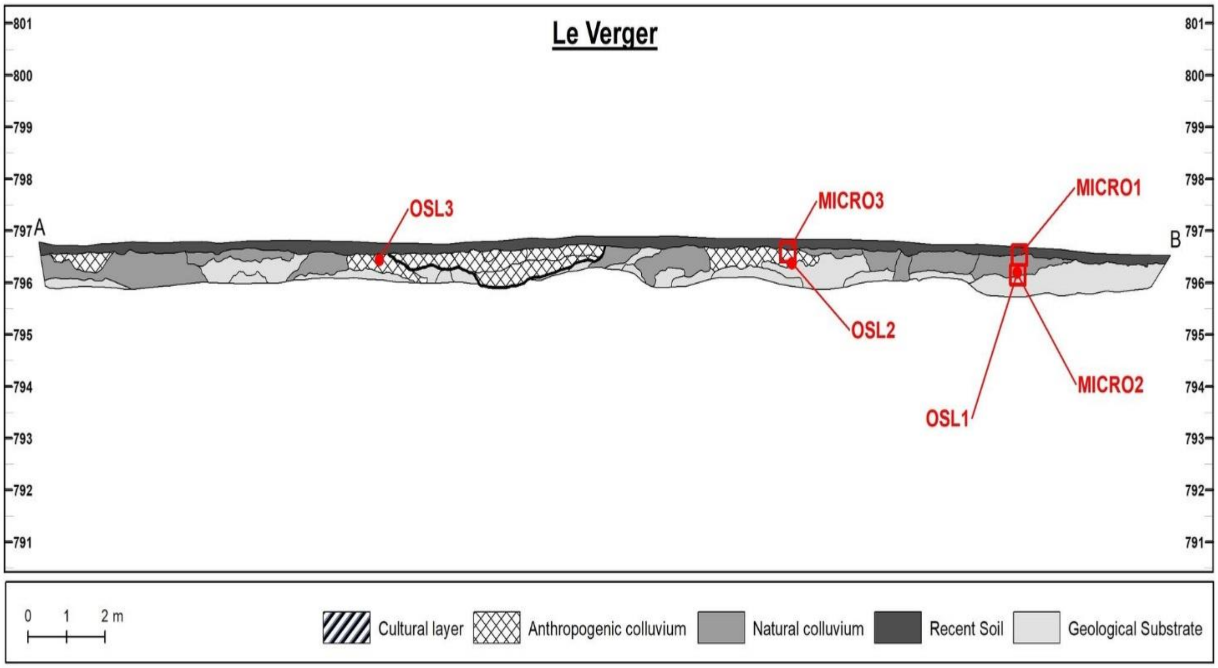

Figure. 3. General observed categories Le Verger with sampling positions. Recent soil as MICRO1 (0-25 cm) and MICRO3 (0-25 cm); natural colluvium as MICRO1 (0-25 cm) and MICRO2 (50 cm), and anthropogenic colluvium as MICRO3 (0-25 cm), OSL1 (50 cm), OSL2 (45 cm), and OSL3 (40 cm).

3.4.1.5. Organisms

Human activities such as modern agriculture, land-use changes, and pollution are changing dramatically over large scales flora and fauna of the soil. For example, Ramankutty et al. (2000) reported that, by the year 2000, cropland and pasture covered 12 and 22% of the Earth's ice-free land surface. This means that more than one-third of the earth's surface is impacted directly by agricultural activities. Even more strongly, Ellis and Ramankutty 55 reported that, by the early 2000s, anthropogenic processes altered >75% of the global, ice-free terrestrial biosphere. Ellis and Ramankutty (2008) also found that only ~11% of net primary production could be attributed to pristine natural processes unaffected by human activity, while almost 90% of the integrated terrestrial net primary production and 80% of tree cover on a global basis were considered anthropogenic biomass. Imhoff et al. (2004) reported similar observations, attributing one-third of the net primary production to human consumption. Human activities not only altered the biodiversity and control productivity parameters.

3.5. Historical maps

Historical maps have the potential to complement other spatial research techniques, such as remote-sensing, thereby facilitating holistic investigations of archaeological landscapes (Rondelli et al., 2013). Geographical information systems (GIS)-based methods are essential to transforming old and sometimes forgotten documents into spatial data for multi-method analysis, including sources that are difficult to compare as discrete documents (Wheatley and Gillings, 2002). GIS allows maps, plans, and other features to transform into digital vector data with spatial coordinates, points, lines, and polygons that can store additional attribute values along with x, y, and z coordinates. Vector data can be extracted from historical documents and integrated with those from other sources (Green et al., 2018), such as remote sensing data (Petrie et al., 2019), and, importantly, can be combined with digital navigation tools to facilitate archaeological fieldwork. Many GIS tools are open source and open access. They can be combined with other accessible data sources, such as Google Earth Imagery, dramatically improving cultural heritage landscape data resolution in many parts of the world (Smith and Chambrade, 2018). Weathering products may differ depending on the climate at the time of weathering or rock exposure (Chesworth et al., 2004). Weathering, alteration, soil accumulation, and evolution rates govern by climates like temperature, availability of water, and biotic factors (Birkeland, 1999). The amount of precipitation is substantial due to the leaching process to transfer silica, clay, and carbonates from the top of soils too deep by water, resulting in soil development (Graham and O'Geen, 2010).

Analysis in a GIS environment is an extensive spatial analysis, besides the extraction of statistics regarding the relation of settlements to the aspect, slope, and relief height. The distance of settlements from natural resources could calculate by applying buffer zones around the quarries and the water springs (mainly springs existing in the mountainous areas). Finally, GIS tools will employ to construct predictive habitation models for each phase of the periods to locate sites that could host a similar type of settlements. All the environmental factors (height, aspect, slope, distance from watersheds, distance from water springs, distance from quarries, geology, distance from chert sources, least-cost paths) could affect the choice of habitation in ancient periods. In recent years, GIS has experienced explore growth, and archaeology has been one of many disciplines to have been caught up in its technological vortex. The GIS multiplier (Conolly and Lake, 2006) in archaeology is in full swing. The rapid diffusion of GIS technology within archeology, tentatively forecast just a few years ago (Harris and Lock, 1990), has been remarkable. Archaeological data have a dual nature, as they are distributed in space and time. Given the nature of most archaeological data, GIS technology is probably the most flexible and complete system for analyzing the spatial context of historical and pre-historical data (Scianna and Villa, 2011).

3.6. Anthropogenic soils

Since they first set foot on the Earth's surface, humans and their hominid ancestors have affected soils. The degree of effect humans have on soils varies from the most subtle, which could include simply walking across the soil, to the most dramatic, such as wholesale removal, mixing, or burial associated with urbanization. Butzer (1982) presents very useful summaries of the history and nature of such influence in a geoarchaeological context. Geoarchaeologists can be confronted with soils subjected to a wide degree of anthropogenic alteration. In theory, the detection of these alterations and their differential distribution can be used to determine site boundaries, define stratigraphic relationships, delimit intrasite activity areas and features, and aid in their functional interpretation. The primary challenge is detecting the human-induced alteration and then, of course, interpreting it. In a very broad sense, the detectability of human impact is roughly proportional to the degree of effects; very subtle alterations are difficult or impossible to detect, but more substantial changes are more pronounced. As in most other aspects of archaeology, interpreting the meaning of anthropogenic effects on soils is much more problematic. The study of human impacts on soils is one of the oldest applications of soil studies in archaeology, particularly in regions with a long history of significant human modification of the environment. The topic is also an essential part of soil science and agriculture. As a result, there is an extensive literature on the subject, especially for the Old World. There may be more writing on this aspect of soil research in archaeology than on all others combined. The topic is of such interest because human impacts on soils can be so obvious and pervasive in archaeological contexts; recognizing human impacts is critical in sorting out artificial versus natural pedogenic and other geogenic processes; it provides another avenue of research into understanding the relationship between humans and their environment, especially the landscape; and it offers another means of getting at human behavior, either directly, as in studies of mound construction or agriculture, or more indirectly, as in studies of human induced soil erosion. Regardless, the subject has long been of interest in archaeology and geoarchaeology.

The impacts of human activities exist in both urban areas and natural ecosystems. Our knowledge of how human activity affects urban soil has expanded considerably, but gaps still exist concerning the influences on anthropogenic soils (Lehmann and Stahr, 2007). Most risks in urbanized areas have been associated with high amounts of Cd, Cr, Cu, Hg, Ni, Pb, and Zn, because the underlying human factors are similar in most urban areas. Differences tend to be limited to toxic element concentrations, soil residence times, and geological conditions. Due to its increasing importance, many studies were published on the effects of urbanization in Central Europe. In Austria, several pollutant surveys were carried out in cities such as Linz and Upper Austria (Weiss et al., 1994). A complex report was published about the heavy metal content in the Austrian economic cycle. Extremely high amounts of Cd and Hg content were typical for the entire country due to the weathering processes of eluvial bedrock (Reisinger et al., 2009). Moderate Cu, Pb, Zn contamination was found in the urban soils of Vienna by Simon et al. (2012). In the Czech Republic, the distribution of 21 elements in the topsoil of Prague was investigated. Based on results, the blood Pb level of 3–6 years old children was the only biomarker significantly higher than the control group values (Zimová et al., 2001). Debnárová and Weissmannová (2010) analyzed Cd, Cu, Pb, and Hg content in soils of roads in Brno. They concluded that the city environment was not contaminated compared to selected pollution factors. In Ostrava, Weissmanová et al. (2015) investigated the total element concentrations in 0–20 cm depths, and the following order of concentration was established: Hg b Cd b Cu b Pb b V b Zn b Mn. In Poland, a booklet about SUITMA's of 10 cities was published by Charzyński et al. (2013) according to land use categories. The SUITMA7 conference was held in Torun in 2013 (Morel et al., 2015). Zawadzki et al. (2016) created a method for detecting soil pollution from long-range and local transport of atmospheric pollutants using soil magnetometry. In a comparative case study, Hulisz et al. (2018) found that despite the significant habitat and historical differences between the medium-sized Toruń and Zielona Góra cities, most of the urban soils are characterized by similar morphology and properties. The Swiss Soil Monitoring Network (NABO), which monitors 102 sampling sites (Desaules, 1993), has been operating in Switzerland since 1985. Researchers in this region are more concerned with measuring PAHs or studying floodplain areas due to topographical features (Amossé et al., 2014). In Germany, Blume and Hellriegel (1981) measured 8 times higher Pb content and 1.5 times higher Cd content than natural background concentrations in the urban soils of Berlin. Several articles about the qualitative interpolation of the limit value overruns (Nathanail et al., 1998; Norra et al., 2002) and GIS assessments (Birke and Rauch, 1997; Norra et al., 2002) have been published. Lehmann and Stahr (2007) summarized the general anthropogenic soil characteristics and classified them by the amount of human influence. Meuser (2010) detected that the concentration of heavy metals decreased with the distance and the depth of soil. In Slovakia, the toxic elements and PAH, PCB contents of soils were examined in the capital city. Sobocká et al. (2000) have developed the inclusion of anthropogenic soils in the Slovak morphogenetic Soil Classification System. Sobocká (2008) investigated the connections between Slovakian Antrozems and Technosols. Bavec et al. (2015) investigated the soils of Idrija, Slovenia, for ten elements (As, Cd, Co, Cr, Cu, Hg, Mo, Ni, Pb, Zn); they discovered extremely high Hg values in 0–20 cm topsoil layer. PAH comparative studies have also been carried out in Ljubljana (Morillo et al., 2007) to compare Glasgow and Turin's contamination levels to the Slovenian capital's soils. Glasgow proved to be the most polluted out of the three cities, but the various climatic factors and the amount of organic matter could be influencing factors. In Hungary, total element results were published about Budapest soils (Kádár, 1995; Salma and Maenhaut, 2006).

3.6.1. Soils with strong human influence (Anthropogenic)

Archaeology studies the human past from its material remains, most of which are made of or found within soils and sediments. Past human actions impact the soil record, as seen through relics of changes in soil characteristics and sedimentation changes and the presence of archaeological features and artefacts preserved within modern soils. Soil and sediment conditions control what survives in the burial environment and what decomposes and influence all archaeological sites, artefacts, and ecological remains. The study of these remains, through survey, excavation, and post-excavation analyses, informs our understanding of past cultures and environments, providing insight into how people have interacted with the soil both directly, through settlement, land use, and monument construction, and indirectly, by altering local ecosystems over time (Holliday, 2004). For these reasons, it is possible to classify them as a specific sub-category of anthropogenic soils – Anthrosols and Technosols (Howard, 2017).

3.6.1.1. Anthrosols

Anthrosols (IUSS Working Group WRB, 2014) comprises soils modified profoundly through human activities, such as adding organic or mineral material, charcoal or household wastes, or irrigation and cultivation. The group includes soils otherwise known as Plaggen soils and Paddy soils which many of them correspond to Highly cultivated soils and anciently irrigated soils.

a) Regional distribution of Anthrosols

Anthrosols are found wherever people have practiced agriculture for a long time. Anthrosols with plaggic horizons are most common in northwestern, central Europe. Together with Anthrosols with a terric horizon, they cover more than 500 000 ha. Anthrosols with irragric horizons are found in irrigation areas in dry regions, e.g., in Mesopotamia, oases in desert regions of Central Asia, and parts of India. Anthrosols with an anthraquic horizon overlying a hydragric horizon (paddy soils) occupy vast areas in China and in parts of South and Southeast Asia (e.g., Sri Lanka, Viet Nam, Thailand, and Indonesia). Anthrosols with hortic horizons are found all over the world where humans have fertilized the soil with household wastes and manure. The Terra Preta de Indio in the Amazon Region commonly has a pretic horizon.

b) Management and use of Anthrosols

Plaggic horizons (Zikeli et al., 2005; IUSS Working Group WRB, 2014) have favorable physical properties (porosity, root penetration, and moisture availability), but many also have less satisfactory chemical characteristics (acidity and nutrient deficiencies). Rye, oats, barley, potato, and more demanding sugar beet and summer wheat are common crops on European Anthrosols with a plaggic horizon. Before the advent of chemical fertilizers, rye yields were 700–1 100 kg/ha or 4–5 times the quantity of seed used. Today, these soils receive generous doses of fertilizers, and average per-hectare yield levels for rye, barley, and summer wheat are 5 000, 4 500, and 5 500 kg, respectively. Sugar beet and potato produce 40–50 tonnes/ha. They are increasingly used for silaging maize and grass; per-hectare production levels of 12–13 tonnes of dry maize silage and 1013 tonnes of dry grass are considered normal. In places, Anthrosols with plaggic horizons are used for tree nurseries and horticulture. The good drainage and the dark colour of the surface soil (early warming in spring) make it possible to till and sow or plant early in the season. Soils with deep plaggic horizons in the Netherlands were in demand for tobacco cultivation until the 1950s. Many garden soils, e.g., in Europe and China, have a hortic horizon. They have been enriched with organic manure. Kitchen soils are another group of Anthrosols with a hortic horizon. Well-known examples are situated on river terraces in southern Maryland, United States of America, and along the Amazon River in Brazil. They have deep, black topsoils formed in layers of kitchen refuse (mainly oyster shells, fish bones, etc.) from early Indian habitations. Many countries possess small areas of soil that early inhabitants modified. All hortic horizons provide a good habitat for soil fauna.

Wet cultivation of rice leads to the development of an anthraquic horizon and, after a long time of management, to an underlying hydragric horizon. Puddling wetland rice fields (involving destruction of the natural soil structure by intensive tillage when the soil is saturated with water) is done intentionally, inter alia to reduce percolation losses. Anthrosols with irragric horizons are formed as a result of prolonged sedimentation (predominantly silt and clay) from irrigation water, and their thickness may reach 100 cm. A particular case is found in depression areas where dryland crops are commonly planted on constructed ridges that alternate with drainage furrows. The original soil profile of the ridge areas is buried under a thick layer of added soil material. In parts of Western Europe, notably in Ireland and the United Kingdom, calcareous materials (e.g., beach sands) were carted to areas with acid Arenosols, Podzols, Retisols, and Histosols. Eventually, these modified surface layers of mineral material turned into terric horizons that gave the soil much improved properties for arable cropping compared to the original surface soil. Recently, terric horizons are created by single additions of mineral material that is thoroughly mixed into the original soil, e.g., in southern Italy. In Central Mexico, deep soils were constructed of organic-matter rich lacustrine sediments, thus forming a system of artificial islands and channels (chinampas). These soils have a terric horizon and were the most productive lands of the Aztec empire; now most of these soils are affected by salinization. Typical for Amazonian Dark Earths (Terra Preta de Indio) is the pretic horizon created by adding charcoal, plant residues, and kitchen refuse.

3.6.1.2. Technosols

Technosols combine soils whose properties and pedogenesis are dominated by their technical origin. They contain a significant amount of artefacts (something in the soil recognizably made or strongly altered by humans or extracted from greater depths) or are sealed by technic hard material (hard material created by humans, having properties unlike natural rock) or contain a geomembrane. They include soils from wastes (landfills, sludge, cinders, mine spoils and ashes), pavements with their underlying unconsolidated materials, soils with geomembranes and constructed soils. Technosols are often referred to as Urban or mine soils. They are recognized in the Russian soil classification system as Technogenic superficial formations, and in the Australian soil classification, they are included in Anthroposols (Ivanov et al., 2009; IUSS Working Group WRB, 2014).

a) Regional distribution of Technosols

Technosols are found worldwide where human activity has led to the construction of artificial soil, sealing of natural soil, or extraction of material usually not affected by surface processes. Thus, cities, roads, mines, refuse dumps, oil spills, coal fly ash deposits, and the like are included in Technosols (Ivanov et al., 2009; IUSS Working Group WRB, 2014).

b) Management and use of Technosols

Technosols are strongly affected by the nature of the material or the human activity that placed it. They are more likely to contain toxic substances than soils from other RSGs and must be treated with care. Many Technosols, particularly those in refuse dumps, are currently covered with a layer of natural soil material to permit revegetation. The soil remains a Technosol, provided that the requirement of having ≥ 20% (by volume, weighted average) artefacts in the upper 100 cm of the soil surface or to continuous rock or technic hard material, a cemented or indurated layer, whichever is shallower, is met (Ivanov et al., 2009; IUSS Working Group WRB, 2014; Schad, 2018).

4. Methodology

4.1. Analysis of anthropogenic soil

The investigation of anthropogenic soils stands as one of the most extensively employed methodologies for their study in the present era. A century ago, the primary focus was directed towards phosphorus and its various compounds within the soil matrix. This emphasis emerged due to the phenomenon wherein phosphorus, once introduced into the soil in the form of phosphate, assumes an immobile state, displaying remarkable stability that facilitates its preservation within the soil over millennia. Phosphorus serves as a pivotal indicator of human presence and activities, as it remains intertwined with human endeavors across the lifespan. Throughout antiquity, the subsequent constituents have historically served as sources of phosphorus: human organic waste (including bones, meat, plants, and organic structural materials), human interments, fertilizers (comprising organic waste, manure, and dung), as well as ash. Furthermore, a spectrum of additional elements stemming from human actions encompass carbon, nitrogen, sodium, calcium, potassium, magnesium, sulfur, copper, zinc, and an array of other elements. (Holliday and Gartner, 2007). These elements can be studied together. Such an analysis is called a multi-element analysis. These analyses take many forms; today the most used devices to obtain the data for this analysis are XRF (field-based or lab-based) and mass spectrometry. In general, the essence of this analysis is to obtain information about the broadest possible range of anthropogenic elements so that their presence in soil or sediments can be interpreted.

Numerous scholarly syntheses have incorporated multi-element analysis as an integral facet within the examination of anthropogenic soils. These reviews have primarily concentrated on the archaeological elucidation of the prevalence of anthropogenic elements. The categorization of chemical constituents was predicated on chronological epochs, practical applications, and the typology of archaeological sites (Wilson et al., 2008; Oonk et al., 2009a; Canti and Huisman, 2015; Lubos et al., 2016; Pastor et al., 2016). In the present study, multi-element analysis is harnessed, among other utilities, within the ambit of investigating abandoned medieval settlements, particularly focusing on derelict agricultural fields. Noteworthy within this research paradigm is the undertaking of extensive spatial sampling encompassing several hectares of forsaken medieval field systems. Comparable endeavors of this nature are relatively uncommon on a global scale (Kristiansen and Amelung, 2001; Nielsen and Kristiansen, 2014). The successful execution of such research mandates a confluence with the annals of agrarian history and agrarian geography (Klír, 2008). The methodologies employed in our study are outlined below:

a) Pedological description and characterization of horizons; b) Portable X-ray fluorescence; c) Micromorphology; d) Magnetic properties; e) Optically Stimulated Luminescence (OSL) dating; f) Dataset characteristics.

4.2. Pedological description and characterization of horizons

The pedological characterization of the samples imparts significant insights into the intrinsic composition of the soil record. Within this characterization process, the primary focus pertains to elucidating the color, alongside certain other pertinent pedological attributes. The coloration of sediments is discerned in both moist and dry states through referencing the Munsell soil color chart. Soil color, in conjunction with additional factors encompassing texture, structure, and consistency, has played a pivotal role in demarcating and defining soil strata, as well as grouping soils within the framework of the soil classification system (Liles et al., 2013; Sawada et al., 2013; Soil Survey Staff, 2014; USDA and Soil Survey Staff, 2010). Notably, soil color serves as a fundamental determinant for identifying stratigraphic horizons within a profile and classifying distinct soil types within a given geographical domain. Routine assessment of soil color has conventionally been carried out in the field by visually juxtaposing a soil sample against reference chips from standardized color charts (Munsell, 1905).

4.3. Portable X-ray fluorescence

Portable X-Ray fluorescence (pXRF) is a non-destructive analytical technique that provides near-instantaneous elemental analysis of materials. This technique is unique to the elemental composition of the sample. Because each element has its characteristic, and pXRF can tell exactly what elements are in the sample and in what quantity, can be operated in the field anytime (anywhere), and provide fast acquisition of geochemical data for rapid delineation of anomalous zones and the in-depth, quantitative analysis of metal content for geochemical mapping. (Potts et al., 1997; Kalnicky and Singhvi, 2001; Markowicz and Van Grieken, 2002; Sitko, 2009).

In this research, we processed the analytical stage this way: we dried the samples at 40 °C for 24 hours. Then, the material was sieved on a 2 mm mesh sieve, and the resulting fraction was grounded in a porcelain mortar. We used a portable ED-XRF (pXRF) analyzer (the device model was “Delta Professional” by Olympus InnovX). The mode “Soil Geochem” was used, and every sample was measured for a 30 s by 10 kV beam (better measurement of lighter elements) and for 30 s by 40 kV beam (better measurement of heavier elements). Results are in weight ppm. The quality of the device measurements was successfully tested on 55 reference materials. This process was used in several previous studies (e.g., Horák et al., 2018; Janovský et al., 2020a,b; Danielisová et al., 2022; Poledník Mohammadi, 2023). Such processes are in good reliability with more developed and established laboratory techniques (Save et al., 2020).

4.4. Micromorphology

In archaeology, the study of sediments and soils has been shown to be an essential component of environmental reconstruction which may concern either palaeolandscapes and human impact at a regional scale, or site formation processes ruled by both natural factors and human activities (Gladfelter, 1981; Butzer, 1982; Stein and Farrand, 1985). To achieve one or both of these objectives, specialists in sedimentary archaeology have developed various approaches concerning their academic origin and, depending on their laboratory facilities. Scientists with somewhat different competencies are now facing a particular challenge: to demonstrate the sagacity of their methodological choice and the efficiency of their approach. In recent years, soil micro morphologists have striven to meet the challenge by demonstrating that the microscope was an essential tool to analyze ancient soils and site formation processes (Courty et al., 1989). The objective of this paper is to analyze the present situation of soil micromorphology in archaeology by considering: (i) how this approach was developed, (ii) how it has enriched our knowledge of archaeological sediments, and (iii) what is the present situation. Although the future of soil micromorphology in archaeology is promising, it may be worthwhile to discuss, in conclusion, how this relatively young method of investigation should progress to achieve its full maturity rapidly. Before entering the debate, it may be useful to outline the method. Soil micromorphology (Bullock et al., 1985) is the study under the optical microscope of thin sections prepared from undisturbed and oriented samples after they have been impregnated by synthetic resin. For efficient coordination between field observations and microscopic investigations, thin soil sections have to be larger (ca. 12 x 7 cm or more) than the standard petrographic ones but have the same thickness (25 pm). A continuous observation from the field scales down to high magnification, permitted by scanning electron microscopes, allows an exhaustive characterization (nature, shape, size, frequency, etc.) of elementary components and the study of their arrangement.

A high level of significance is given to specific attributes, which are subdivided according to their origin into three well-defined groups: i) Sedimentary features, which are diagnostic of the source of the sediments, the mode of transport, and depositional conditions. ii) Pedological features that give information about the dynamics of each soil-forming process and about the interaction of these processes through time. iii) Anthropogenic features related to human activities can be identified at various scales, such as mineral or organic components of human origin, or which may correspond to specific fabrics induced by human transformations. Both human-induced fabrics and anthropogenic components can have been produced intentionally or accidentally.

4.4.1.The advancement of soil micromorphology in archaeology

Two decisive periods have marked more than half a century of continuing research in archaeological sedimentology. The first was in the late 1950’s when interest in prehistoric sediments increased considerably, especially in Europe (Miskovsky, 1974; Farrand, 1975; Laville, 1976; Campy, 1982). Quaternary geologists and prehistorians worked together on the chronostratigraphy of prehistoric sequences, emphasizing the paleoclimatic implications. They gave little consideration to the regional significance of the sedimentary signal recorded at the micro-regional scale of archaeological sites. Field stratigraphical interpretations were supported by analytical data, the validity of which had never been evaluated. Particle size analysis was routinely performed because it is easy to handle both technically and scientifically. For academic reasons, individuals sharing a common interest in archaeological sediments have rapidly formed a scientific community that has been rather independent of related disciplines in earth sciences (classical sedimentology, geochemistry, pedology, etc). Consequently, archaeological sedimentology has not fully profited from the technical and scientific progresses accomplished in these various fields. Furthermore, the results achieved in archaeological sedimentology have not been critically evaluated by the larger community of earth science specialists. This situation may explain why soil micromorphology was not introduced at this stage in archaeological sedimentology, although the microscopic approach was entering its golden age in soil science and was already familiar to soil scientists dealing with archaeological soils (Romans and Robertson, 1983). An important change marked archaeological sedimentology in the late 1970's when Karl Butzer, followed by others, clearly stated that archaeological sediments are singular because they relate to interactive processes ruled by human beings and natural factors (Butzer, 1982). Geoarchaeologists suddenly realized that past humans had contributed to the sedimentation process of archaeological sites not only with lithics, bones or plants but with mineral components which may have substantially affected the original sedimentary signal (Stein, 1985). This new generation of archaeological sedimentologists has much debated the necessity of a careful examination of sediments to identify the cultural components of the site matrix (Stein, 1985). They have, however, never considered the necessity of adapting methods and related techniques to achieve the new goals. Using methods similar to those of their predecessors, they have mostly been able to detect anthropogenic influence on sediments but have not recognized the human activities involved. At the same time, soil micromorphology was introduced into archaeology by earth scientists who were external to this new trend of archaeological sedimentology. Familiar with the microscopic scale from their basic training at university, they naturally thought using thin sections was necessary when facing archaeological sediments and soils. They spontaneously joined the group of soil micro morphologists and have remained highly pragmatic when characterizing sedimentary signatures of cultural activities. Evolving rather far from the theoretical debate of archaeology, they realized that the micromorphological soil approach was throwing new light on contextual archaeology (Goldberg, 1979, 1981; Courty and Fedoroff, 1982, 1985; Fisher and

Macphail, 1985). At the same time, following the lead of Andre Leroi-Gourhan, French archaeologists have been discussing the dynamics of the formation of living floors. They have essentially taken into consideration the spatial distribution of artefacts and their typological and technological characteristics. In contrast, they have made little use of the sedimentary attributes because the close relationship between the sedimentary matrix and cultural processes was still poorly documented (David et al., 1973; Rigaud, 1979; Audouze, 1985).

Soil micromorphology is the study of soil substrate via thin oriented sections. While the analytical method will show the general composition of the soils, the soil micromorphology may reveal much more information related to the primary and post sedimentary formation processes. More than 20 undisturbed samples were prepared from the main palaeosol/pedo complex horizons to study the soil micromorphology. Samples will be labeled, according to the subunits (minimally 10 samples were already taken and are now available in the forms of thin sections). The samples were packed into clink foil, transported to the laboratory, dried, and impregnated in a vacuum by resin Polylite 2000. After curing a thin section of the thickness of 30 micrometers, they were done from them. Those sections were studied under the polarizing microscope at magnifications ranging 16 – 400 × and described according to Stoops (2003; 2010).

4.5. Magnetic properties

Magnetic susceptibility provides a measure of the effectiveness of the potential application of magnetic surveys (through the estimation of the normalized Le Borgne Contrast, namely the variation of the magnetic susceptibility with depth) and an index of the past workshop activities in an area. Measurements of the magnetic susceptibility and the frequency-dependent susceptibility (namely the variation of MS with the frequency of an induced magnetic field) indicate the intensity of a site's occupation (Clark, 1990). Coupled with results of chemical properties of soils. It is possible to characterize the type of workshop activities (e.g. increase in manganese content can be associated with glass workshop activities) or differentiate areas used for animal husbandry, midden deposits, foundation trenches, cultivation, cooking, etc. Even the chemical stability of certain organic chemical compounds (e.g., coprostanol) may act as a biomarker of the human presence at a particular location (Sarris, 2008).

The choice of the technique depends mainly on some factors: the type of the targets, their lateral and vertical dimensions, their deposition depth, and type/properties of the surrounding soils (to be able to create a significant signal, contrast, or "anomaly"). Architectural features such as stone/brick structures, roads, walls, built/chambers or rock-cut tombs can be relatively quickly resolved through soil resistance or GPR surveys. Brick structures or architectural features that are either burnt or contain residues of heating/burning, kilns, workshop facilities, slag deposits, metal concentrations, and sometimes roads, walls, and fortifications can be detected through magnetic and electromagnetic techniques. ERT, GPR, and microgravity are especially useful for the identification of vaults, caves, chamber tombs, and fissures. Shallow depth surveys usually employ magnetic, soil resistance techniques and GPR. In cases where deeper penetration is required, GPR, ERT, and seismic approaches are more appropriate (Linford et al., 2011; Sarris, 2008). The image processing techniques play a significant role in the visualization of the results of the geophysical surveys as the ultimate goal is to provide images that depict the underlying features at their exact location and horizontal/vertical extent in a way that can approach the results of an after-the-excavation plan. This objective can be achieved through several filtering/convolution processes, the employment of synthetic models or inversion algorithms, or other image processing functions (Sarris, 2008). In cases where multiple datasets are available for the same region, composites can be made using visualization techniques similar to those used in satellite remote sensing (Böniger and Tronicke, 2010). Even more impressive visualization can be created through the fusion of geophysical data with satellite remote sensing or aero-photogrammetric data and lidar or terrestrial 3D laser scanning (Bem et al., 2011). Indeed, the continuous improvement of high-resolution satellite remote sensing sensors has made their simultaneous utilization possible with conventional geophysical data affecting their resolution and potential in detecting and mapping underground features (Crespi et al., 2011).

The magnetic properties of the soil minerals depend essentially on the Fe content because Fe is 40 times more abundant than the sum of all other magnetic elements in the earth's crust (Coey, 1987), and Fe-oxides such as magnetite and maghemite are ferrimagnetic (Cornell and Schwertmann, 2003) and can be easily identified due to their very intense response to the external magnetic field. Magnetic susceptibility measurements were performed in the Laboratory of Rock-Magnetism in the Institute of Geophysics, Czech Academy of Sciences. Bulk samples were used to measure volume-specific magnetic susceptibility (κ, SI) by using an MFK1-FA Kappabridge device (AGICO, Brno, Czech Republic) (Pokorný et al., 2011). Each sample was measured twice at two operating frequencies, f_1 = 976 Hz and f_3 = 15 616 Hz. Readings of the unconsolidated samples were taken in plastic bags; the measured susceptibility values were normalized by the mass of each sample and expressed as mass-specific magnetic susceptibility [χ, m^3/kg]. Magnetic susceptibility refers to the concentration, size and character of Fe-oxides minerals, and can be detected even in trace quantities in any rock, soil, or even in organic tissue (e.g., Thompson and Oldfield., 1986). Frequency-dependent magnetic susceptibility, χ_{FD}%, is a particular property of ultrafine, superparamagnetic grains, which result from pedogenic processes (e.g., Maher, 1986). This parameter was characterized by the following commonly accepted formula:

$$\chi_{FD}\% = 100 \times (\chi_{LF} - \chi_{HF}) / \chi_{LF} \qquad [\%],$$

where χ_{LF} and χ_{HF} are mass-specific magnetic susceptibilities determined for frequencies f_1 and f_3. (Dearing et al., 1996; Hrouda, 2011).

Magnetic susceptibility refers to bulk sample properties in contrast to (electron) microscopical techniques where only a small fraction of a sample can be analyzed. From the analytical perspective, magnetic susceptibility is frequently used due to its sensitivity, rapidity, ease of sample preparation, comparatively modestly priced instrumentation for data acquisition, non-destructiveness, and in particular the ability to sense grain-size variation in the ultrafine grain-size range. Therefore, magnetic susceptibility parameters are well suited as proxy parameters (e.g., Fialová et al., 2006).

4.6. Optically Stimulated Luminescence (OSL) dating

Optically stimulated luminescence is a dating method based on measuring doses from ionizing radiation. The estimated time of material deposition, i.e., burial is based on a set of parameters that should be measured or suggested separately (humidity, gamma spectrometry of provenance material, estimation of erosion after the burial). Samples were taken from cleaned profiles into metal tubes and beated into the profiles without daylight. Additional bulk samples of the weight of approximately 0.5 kg was taken from the surrounding of the tube. Samples were taped using black tape and aluminum foil to protect the material from the light.

The measurement has been carried out in the Gliwice luminescence dating laboratory (Moska et al., 2021). For dose rate determination, high-resolution gamma spectrometry using an HPGe detector manufactured in Canberra was used to determine the sample's content of U, Th and K. Before measurement, the sample was stored for about 3 weeks to ensure equilibrium between gaseous 222Rn and 226Ra in the 238U decay chain. Each measurement lasted for at least 24 h. After subtraction of the detector background, the activities of the isotopes in the sediment were determined using IAEA standards RGU, RGTh, RGK. Guerin et al. (2011) calculated dose rates using the conversion factors. For the beta dose rate the cosmic ray dose rate of the site was determined as described by Prescott and Stephan (1982). We assumed that the average water content was (15 ± 5) %. A mean kα-value of 0.04 for silt-sized quartz (Rees-Jones, 1995) was used for further calculations. All necessary data for dose rate calculations are presented in Tables. For OSL measurements, medium grains of quartz (45–63 μm) were extracted from the sediment samples by routine treatment with 20% hydrochloric acid (HCl) and 20% hydrogen peroxide (H_2O_2) (Aitken, 1998). The quartz grains were separated using density separation with sodium polytungstate solutions, leaving grains of densities between 2.62 g/cm^3 and 2.75 g/cm^3. The grains were sieved before etching with concentrated hydrofluoric acid (HF, 40 min). All OSL measurements were made using an automated Risø TL/OSL DA-20 reader for the OSL of multi-grain aliquots, each of ca. 1 mg. The stimulation light source was a blue (470 ± 30 nm) light-emitting diode (LED) array delivering 50 mW/cm^2 at the sample (Bøtter-Jensen, 2000). Detection was through 7.5 mm of Hoya U-340 filter. Equivalent doses were determined using the single-aliquot regenerative dose (SAR) protocol (Murray and Wintle, 2000). Final equivalent dose (De) values were calculated for all samples using the Central Age Model (CAM) and Minimum Age Model (MAM) (Galbraith et al., 1999) using R package 'Luminescence' (Kreutzer et al., 2012, 2020). CAM model overdispersion parameter was calculated for each sample and for samples were this parameter exceeded 20% MAM were applied. This enabled us to distinguish differences between both models and in turn use the results for final De calculations for select samples. For all samples where MAM were applied, a typical unimodal equivalent dose distribution was not obtained, meaning that those samples do not represent a grouping of adequately bleached samples (Arnold et al., 2007).

4.7. Dataset characteristics

The statistical software R is in version 3.6.0. was applied for the data analyses. The final dataset consisted of at least 334 samples and these elements: Al, Si, K, P, Ti, Mn, Fe, Cu, Zn, As, Rb, Sr, Zr, Pb and LE. The abbreviation LE stands for "light elements" and is an aggregate expression of the content of elements from H to Na, which can be detected by pXRF but cannot be distinguished. Although it is not an elemental content, but rather a quasi-elemental variable, we usually use it in analyses anyway, as it bears proxy information (and usually tends to be connected to the topsoil or organic material (Horák et al., 2018). There were also some unmeasured values in the used dataset (3 samples in the case of P). We computed these missing values using the function impKNNa (R package rob Compositions (Boogaart et al., 2010), which is suited for such tasks when working with geochemical data. There were used mainly exploratory visualization techniques like boxplots and scatterplots. For testing the diversity between categories, we used the Kruskal-Wallis test. We also used multivariate analysis (principal component analysis: PCA). We performed it in two ways: on elemental content data, and on such data after ilr-transformation (ilr-transformation is part of log-ratio transformations suitable for compositional data like geochemical data - Reimann et al., 2008). Both approaches emphasize different aspects of the dataset, and their combination can uncover exciting patterns.

4.7.1.Principal components analysis

To decipher intricate datasets, multivariate methods are employed to diminish their multidimensionality, thereby elucidating a substantial portion of the data's variation. principal component analysis (PCA) involves reducing the dataset's dimensionality while simultaneously preserving and elucidating the maximum amount of interpretable relations, commonly referred to as "variance," among variables (Morrison, 1990). The objective of this task is to identify novel "variables" known as principal components, which are linear combinations of the original dataset's variables. These principal components are successively derived to optimize the explained variance within the dataset while maintaining statistical independence from one another. The process of obtaining these principal components (PCs) entails solving an eigenvalue/eigenvector problem. In this study, the software STATGRAPHIC CENTURION XVI, version 16.1.18 (Statpoint Technologies, Warrenton, VA, USA), was employed to conduct the PCA analysis.

5. Results

5.1. Detection of occupational surface remnants at a heavily eroded site; a case study of archaeological soils from La Terrasse, Bibracte oppidum (Published articles)

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Content

Abstract

The area of La Terrasse is located at one of the higher parts of the Celtic oppidum Bibracte. No traces of building activities, except for the fortification system which surrounds the plateau from three sides, were archaeologically detected and the area can be therefore labeled as "empty space" with an enigmatic history. Multiproxy investigations of sediments in trenches cutting across various parts of the enclosed area and excavated during the 2019 season revealed a complicated history of the formation, being influenced by erosion and by anthropogenic stabilization. Although the recent relief of the La Terrasse area appears quite stable, there is evidence that the site (and Bibracte oppidum in general) was subject to intense erosion in the past and that the former surface with the archaeological soil dated to the Late Iron Age is preserved only as a relict expressed geochemically by the increase of CEC. The reason for the recent surface stability is the presence of the Iron Age ramparts, which enclose the area and protect it against erosion. An OSL sample collected from the surface of the buried archaeological soil dates the overburden not later than to the early Medieval period (AD 561). The archaeological soil represented by the overburden did not reveal any significant geochemical signal indicative of intensive use despite its location in the most suitable and stable area of the site. It is clear that the detection of former surfaces in eroded and exposed archaeological sites and the properties of the archaeological soils is always a complex matter and can only be addressed through a combination of field observations, geochemical and micromorphological proxies.

Introduction

Soil erosion is a topic that has been repeatedly discussed not only in relation to interpretation of archaeological sites but mainly as an important issue for current and by extension future soil sustainability. The fact that the soil surface naturally undergoes erosion regardless of human influence is documented at a number of localities with buried interglacial or interstadial soils (Antoine et al., 2013; Lisá et al., 2014). Climate change is only part of the reason for the increased rate of erosion; the fact that the uppermost part of the landscape formed by non-lithified material (A soil horizon) is excessively prone to erosion is another factor. Evidence for natural erosion events is present within the above-mentioned sedimentary archives. Geomorphological modeling of the landscape, which can be documented retrospectively in some cases, also supports this conclusion. It is well known that people modified the landscape in the past to decrease erosion (Dejmal and Hoch, 2013). The earthworks were generally erected by (pre-)historic people to modify their living environment for a number of reasons such as improvement of quality of life and demarcation of certain areas, or for defense purposes (Moore, 2017a). In some cases, the earthworks also reflect the environmental challenges at the time of construction (Garland, 2020) Human impact on the landscape and soil erosion has been evident since prehistoric times (Dotterweich, 2013). As early as the Mesolithic period, the manipulation of forest vegetation by fire through sedentary hunting and gathering groups could create open areas, woodland shifts and result in intensive soil erosion on a local scale (Hornberg et al., 2005; Putzer et al., 2016; Dietre et al., 2014; 2020). In different parts of the world, under different climatic conditions and different land use histories, landscapes are frequently degraded by surface erosion, riverbed erosion, valley modeling in combination with increasing accumulation of alluvial deposits (Poesen et al., 2003; Lang and Bork, 2006; Dotterweich, 2008; Hoffmann et al., 2009; García-Ruiz, 2010; James, 2013; Vejrostová et al., 2017; 2019) as a consequence of agricultural or mining practices. During the Late Bronze Age and Iron Age until the “Gallo-Roman period” increased alluviation is documented in the Saone Valley (Argant et al., 2011) and, similarly, in the Loire valley, where anthropogenic impact on fluvial environments increased notably since the Gallo-Roman period (Carcaud et al., 2002; Visset, 2011; Gall, 2012). It is also documented in the north-western Alpine foreland, where the main colluviation phases were recently confirmed for middle Bronze Age, Iron Age and the Medieval period (Scherer et al., 2021). The main periods that are detectable in sedimentary records, such as erosion due to agriculture, fire and livestock, occur, as an example, in the early and late Neolithic periods (approximately 5500–2200 BCE) in southern and central Germany, or at 2300 – 500 BCE in SE Switzerland Alps (Dietre et al., 2020) and Northern Alps (Ropke et al., 2011). Other peaks appeared perhaps at the end of the Bronze Age (~1000–1300 BCE), Iron Age (800–15 BC), and at the end of the Roman period (15BC – AD 450 CE) and Middle Ages (AD 450–1500). Increased erosion is usually linked to climate and economic, social and cultural developments. Conversely, minimal soil erosion is detected for the early Bronze Age (about 2000–1600 BCE), the migration period (about 400 / 500–700 CE) and the early Middle Ages (about 700–1000 BCE) (Dotterweich, 2008). However, natural soil erosion also occurred retrospectively as a result of vegetation decline caused by climatic shifts to drier conditions with episodic extreme precipitation events (Li et al., 2010; Vejrostová et al., 2017; 2019; Parma et al., 2015). Increased soil erosion can also be a consequence of long-term climate change and intense pressure on soils. The main aim of this paper is to discuss how to identify the occupational surface remnants at a heavily eroded site and to describe the origin and properties of newly formed archaeological soil. The case study concentrates to the archaeological soils of the oppida Bibracte (Figure. 1) which was intensively occupied from the end of 2nd century to the 1st century BCE. The oppida – large, mostly hilltop fortified settlements – were established during the 2nd century BCE as a new feature of the settlement structure functioning as commercial, political and cultural centers. A Late Iron Age settlement at Mont Beuvray, identified as being the Bibracte oppidum from the written sources, is one of the key sites in oppida research: already excavated during the second half of the 19th century it has been re-excavated from 1984 until today (Guichard et al., 2018). Although the oldest traces and numerous traces of occupation of Mont Beuvray date back already to the Neolithic period (5th millennium BC: Martineau et al., 2011; Guichard and Paris, 2013), the activities in the following periods (until the development of the oppidum) are hardly noticeable (Guichard et al., 2018). Human impact is not necessarily the only factor playing an important role in the process of landscape erosion. Phases of erosion and soil forming intensity in the exposed part of the archaeological site also play a role. In case of Bibracte, the input proxies are mainly the type of subsoil, slope exposure, climatic conditions and anthropogenic influences, including terrain modeling. The output includes the evaluation of the original surfaces on which activities related to human presence at the oppidum took place.

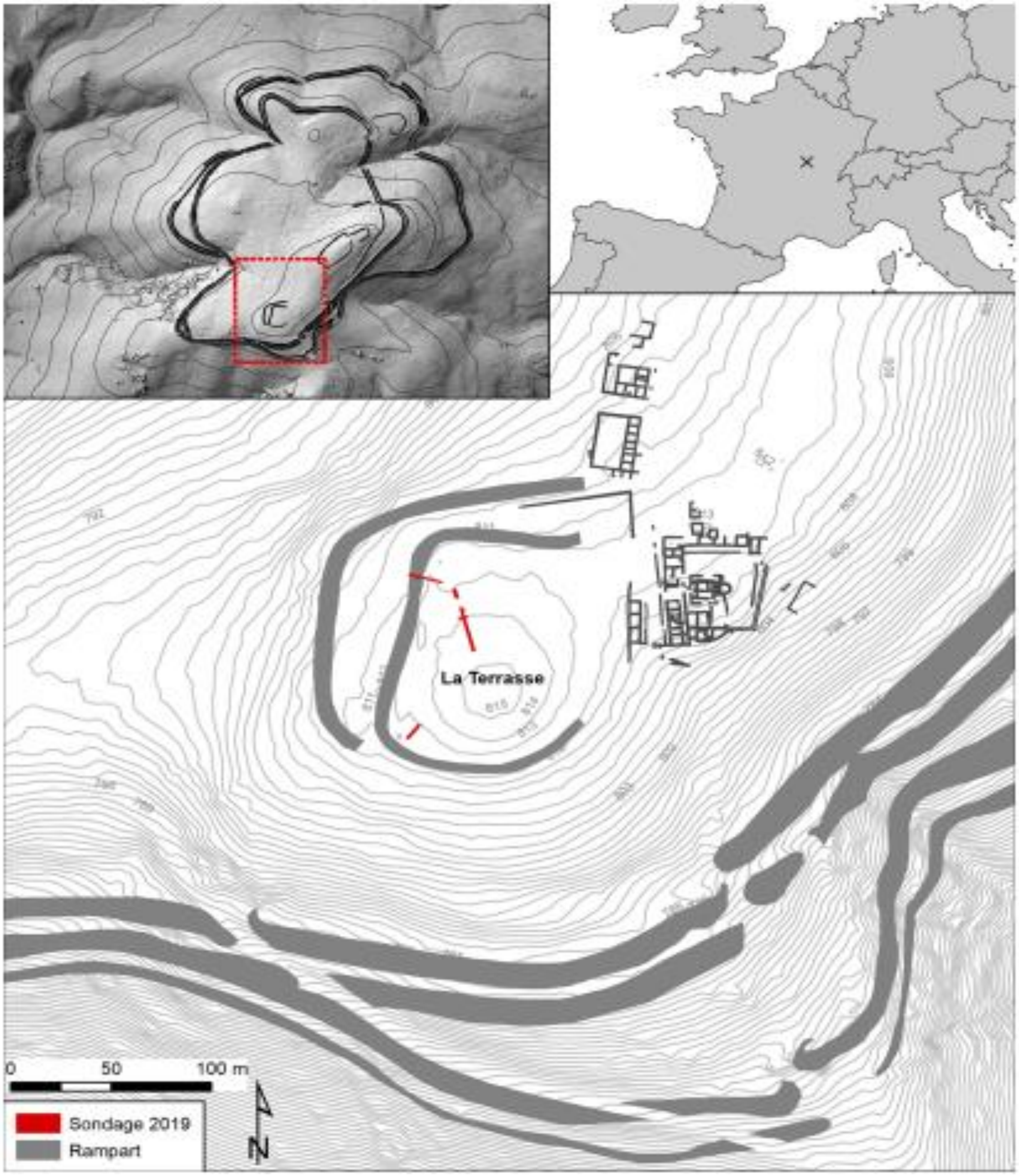

Figure.1. Topographical map of Bibracte with the location of the La Terrasse area (A), the link between the site, ramparts and archaeological features in close surrounding (B) and the detail positions of pedological sondages from 2019 year (C).

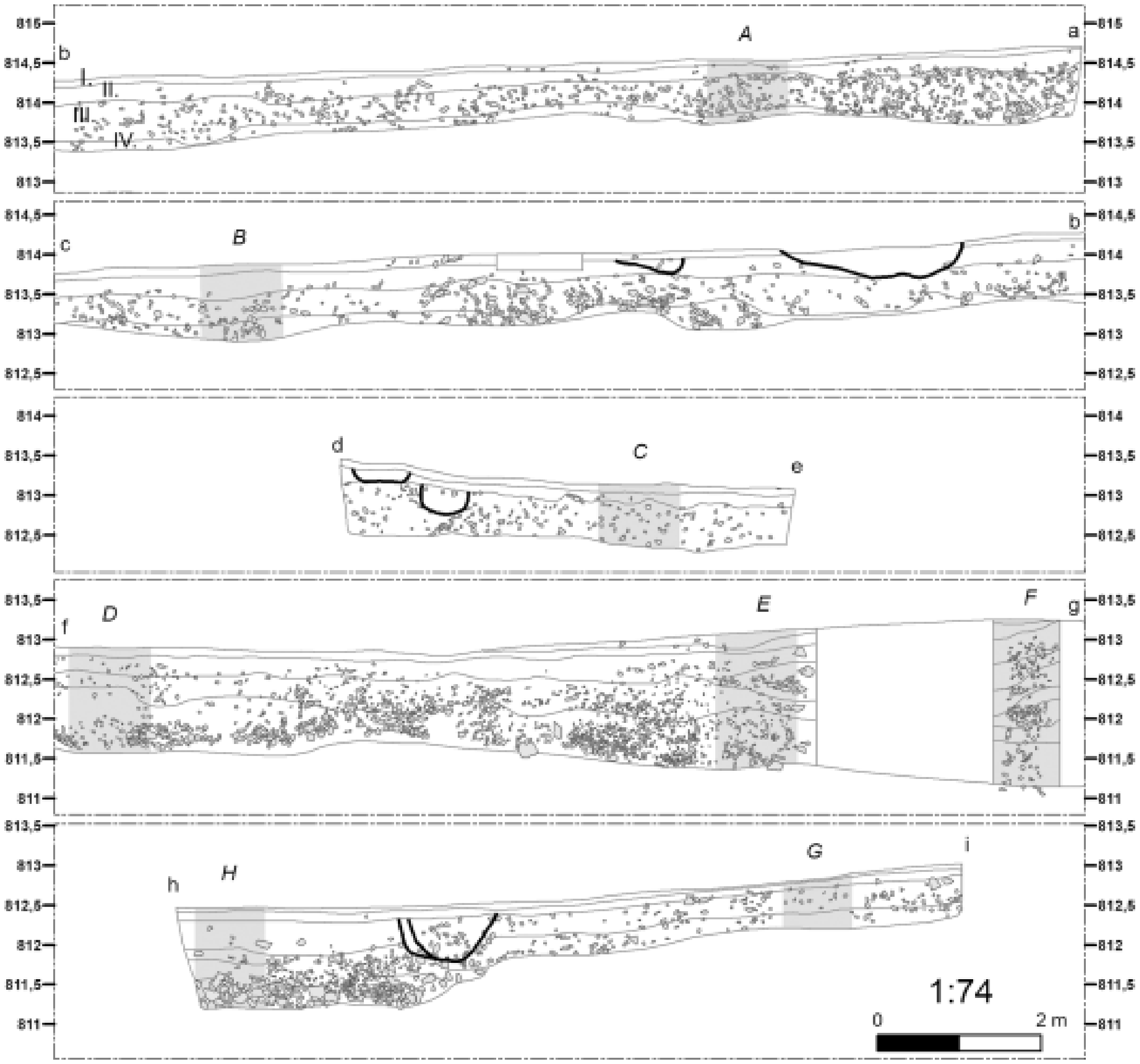

Figure. 2. Detailed archaeological drawings of reopened trenches from 2019 year with the location of pedological sondages.

Table. 1. Quantification of the pottery finds from the test-pits

Test-Pit	Depth (Cm)	Ceramics Number	Weight (g)	Terminus post quem (and the archaeological material on which it is based) Oppidum period (Dressel 1 amphora)
A	20	3	41.30	Late oppidum period (rooftiles)
	30	8	213.70	Late oppidum period (rooftiles)
	40	1	1.00	Late oppidum period (rooftiles)
B	20	2	126.00	Late oppidum period (rooftiles)
	30	4	54.60	Gallo-Roman period (slipped fineware)
	40	3	2.10	Late oppidum period (rooftiles, Dressel 1 amphora)
C	10	3	8.00	Late oppidum period (rooftiles, Dressel 1 amphora)
	20	7	421.00	Late oppidum period (rooftiles, Dressel 1 amphora)
	40	1	2.80	Iron Age or Gallo-Roman? (Light common ware)
D	10	4	5.00	Oppidum period (Dressel 1 amphora)
	20	5	62.60	Late oppidum period (rooftiles, Dressel 1 amphora)
	30	7	77.50	Late oppidum period (rooftiles, Dressel 1 amphora)
	50	1	9.00	Prehistory (coarse handmade pottery)
E	10	3	23.00	Late oppidum period (rooftiles, Dressel 1 amphora)
	20	1	1.20	Late oppidum period (rooftiles)
	30	8	383.20	Late oppidum period (rooftiles, Dressel 1 amphora)
	40	2	1.40	Late oppidum period (rooftiles, Dressel 1 amphora)
	50	2	5.50	Prehistory (coarse handmade pottery)
	60	2	269.00	Oppidum period (Dressel 1 amphora)
	70	2	399.00	Oppidum period (Dressel 1 amphora)
	80	1	2.00	Oppidum period (Dressel 1 amphora)
F	30	2	15.70	Prehistory (coarse and fine handmade pottery)
	40	1	1.60	Undetermined (dark common ware)
	50	3	3.00	Prehistory (fine and coarse handmade pottery) and undetermined (oppidum period?) coarse ware
	70	12	7.90	Oppidum period or broadly Iron Age? (Light coarse ware)
	80	13	30.10	Mainly Prehistory (fine and coarse handmade pottery) with one sherd of oppidum period light coarse ware
	90	14	108.50	Prehistory (fine and coarse handmade pottery), undetermined coarse ware and one sherd of Iron Age (oppidum period?) dark coarse ware
	100	3	4.90	Undetermined (coarse ware and dark common ware, possibly of the oppidum period)
	110	3	6.80	Undetermined (coarse ware and dark common ware, possibly of the oppidum period)
	120	2	3.60	Undetermined (dark common ware, possibly of the oppidum period)
	130	7	25.90	Prehistory (fine and coarse handmade pottery) and undetermined (oppidum period?) coarse ware
	140	7	86.60	Oppidum period or broadly Iron Age? (Light coarse ware)
	200	2	4.5	Dubious: rooftile fragments – probably intrusions
H	10	1	1.70	Uncertain – Iron Age or Gallo-Roman? (Dark common ware)
	50	1	224.00	Oppidum period (Dressel 1 amphora)
	70	43	68.90	Oppidum period (Dressel 1 amphora)
	80	6	30.4	Uncertain – Iron Age? (Light common ware not characteristic of the oppidum)

Materials

Archaeological background

Oppidum Bibracte is a hill-top site on Mont Beuvray (821 m a.s.l. near Autun, Burgundy, France), with intensive settlement dating to the Late Iron Age (end of 2nd century − 1st century BCE). Initially, it consisted of wooden buildings, which were replaced by stone constructions based on Roman concepts in the second half of the 1st century BCE. These stone constructions had a preservation effect on the remnants of the older wooden structures so that in places where stone constructions were not built, the traces of the older wooden structures from pre-roman period hardly survived. The Bibracte oppidum, capital of the Aedui Celtic tribe, was founded at the end of the second century BC and flourished throughout the second half of the first century BC; J. G. Caesar (Caesar, 1917) described the site as by far the largest and the best-provided of the Aeduan towns. The oppidum was initially surrounded by a long rampart system (7 km) that was soon abandoned in favour of a shorter one (5.2 km). The shorter but stronger fortification, with preserved rampart heights of up to 4 m, is contrasted by enclosure systems discovered intra muros, still visible at the summits of La Terrasse and Le Porrey. There is clear evidence for mining activities inside the ramparts, which were abandoned at the latest during the 1st century BCE (Guichard and Paris, 2013). We lack the evidence for agriculture cultivation of crops (and intense cattle breeding) intra muros during the 2nd -1st century BCE (cf. Golánová and Malý, 2020), even if it is documented for the Medieval and recent past (Beck and Saint-Jean Vitus, 2018). Bibracte was a true urban agglomeration: the documented changes in architecture and material culture reflect the political and cultural shifts that took place during its brief existence, marked especially by the erection of buildings in Roman style after the Gallic War (Luginbühl et al., 2014; Szabó et al., 2019). Bibracte reached its peak in the second half of the 1st century BCE, shortly before its rapid abandonment after the beginning of the first century AD in favour of a new city, Augustodunum and was never fully populated again. During the Medieval period, a monastery was built in the centre of the area enclosed by ramparts (Beck and Saint-JeanVitus, 2018) and the 700 m distant hilltop plateau of La Chaume was regularly (certainly since the Middle Ages) used only as a site for annual markets. The St. Martin Chapel, which partly delimits the market area, has retained elements of the 1st century CE temple, followed by Medieval Christian sanctuaries, built at the same place. The area next to La Chaume, which is the location of the markets, is an enigmatic part of the oppidum called La Terrasse.

Geomorphology

The site oppidum Bibracte is located around the top of Mont Beuvray (821 a.s.l.) (Figure. 1), composed of small plateaus and slopes divided by lateral valleys oriented in the NW-SE to W-E directions. The geological substrate is relatively homogenous composed of granitic rocks crosscut by micro-granitic and quartz veins with polymetallic (Pb, Zn, Ag) mineralization (Gourault, 1999; Marcoux, 1986). The southern part of Bibracte oppidum is built of conglomerates and rhyolite (i.e., a volcanosedimentary formation; Ricordel et al., 2007). The soil cover is linked mainly to the geological background and vegetation both intensively influenced by human activities in the past.

The Mont Beuvray itself is geomorphologically complex. So called "intra murros" part of the Bibracte covers 1 884 745.233 m^2. Based on GIS analyses done by J. Geřsl is minimally 71 % of the area under the slope 7 – 30 % and 12 % of that area is under the slope higher than 30 %. Most of the area with the slope up to 7 % slope (17 % of the intra murros area) is flattened by the construction of anthropogenic terraces (Golánová ed., forthcoming). The high percentage of the area under the slope higher than 7 % is expected to be exposed to soil erosion relatively often due to the slope and human action connected with the change of vegetation, but until now we do not know to what extent, how often and how this erosion affected the preservation of archaeological structures in different parts of the oppidum. The area "La Terrasse" located in one of the highest points of the oppidum and without traces of constructions, could serve as a model space for erosion rates in the Holocene in archaeologically exposed sites. The Atlantic Mountain climate and the associated natural vegetation - beech groves in the highest parts, beech-oak grove sessiliflore elsewhere - have determined a climatic pedogenesis locally modified by materials original, different relief and drainage. There were detected generally three main types of soils in relation to geomorphology of the area: (1) soils formed on sandy clay loam in the valley bottoms. These are characterized by the presence of a water table circulating more or less rapidly and undergoing oscillations more or less marked according to the topography; (2) colluvial soils at the level of ruptures slope, formed on scree of eruptive rocks, rich of humus, sometimes hydromorphic. These soils are often aerated and humus-bearing, but difficult to work mechanically due to their stoniness;

(3) brown soils formed on granites, schists or tuffs, sometimes very superficial on the steep slopes and high slopes. Those are light soils rich of humus (Buchsenschutz and Richard, 1993;1996).

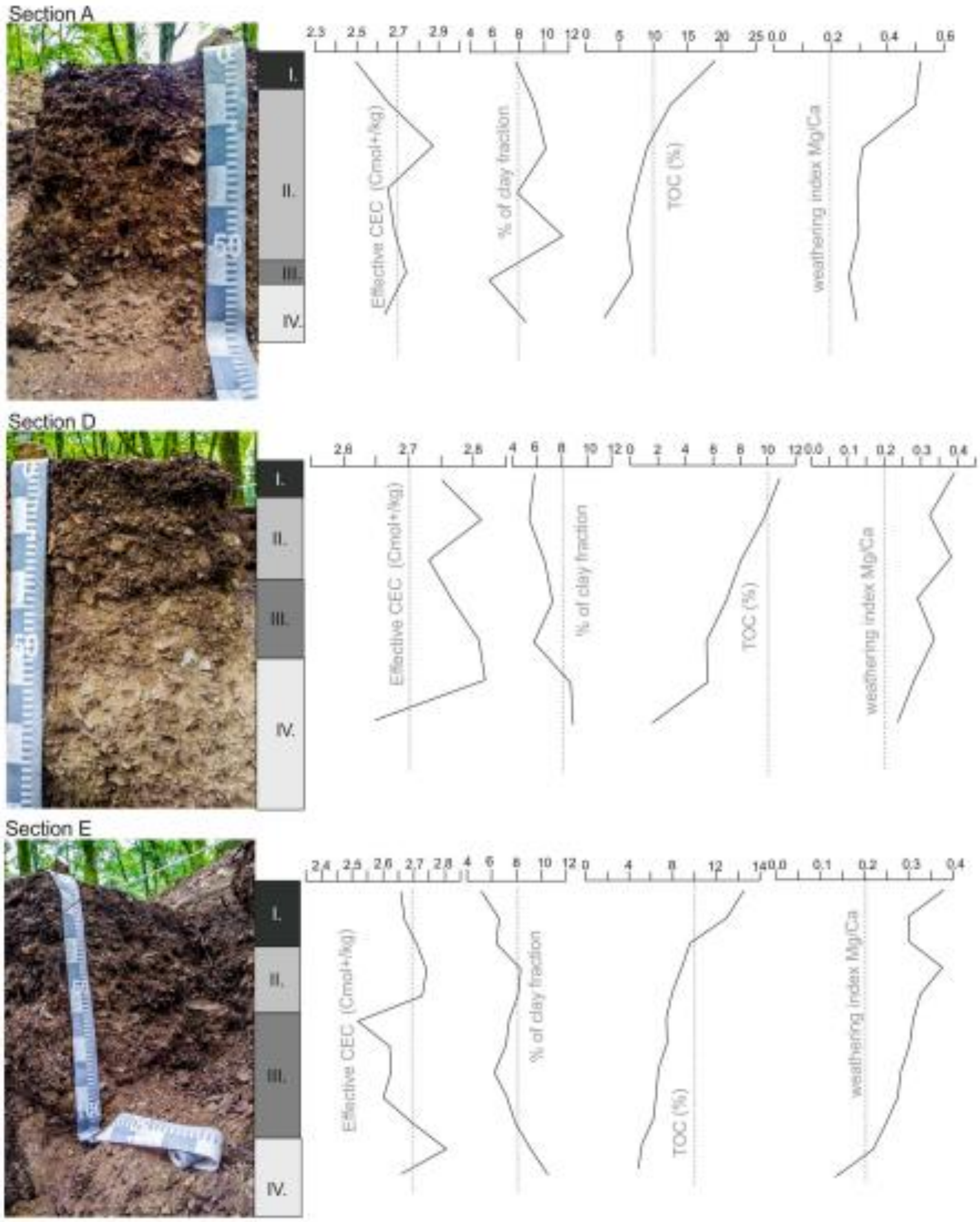

Figure. 3. Drawings and photos of chosen pedological sondages A, D and E together with the TOC, grain size distribution and magnetic susceptibility.

Table. 2. Micromorphological description; Gr-Granular, Bl-Blocky, Sb- Sub angular blocky, Ab-Angular blocky, Ma-Massive, Chm-Chamber, Chn-Channel, Sp- Simple packing, Cdp-Compound packing, Po- Porphyric, Mo- Monic, Cr- Crystallitic. Am-Amphibole, Qu-Quartz, Fsp- Feldspar, Mi-Mica, Cal-Calcite, Pl-Plagioclase, Ser- sericite, Srp-Serpentine, Op-Opaque, Cl-Chlorite, Rf-Rock fragment, Pyr-Pyroxene, Mc-Microcline, Bt-Biotite, Ot-Other.

Section	TA1	TA2	TB1	TB2	TD	TE1	TE2	TH
depth	50 – 56 cm	22 – 40 cm	50 – 60 cm	30 – 40 cm	40 – 50 cm	100 – 110 cm	70 – 85 cm	40 – 50 cm
Micro-structure	Sb, Gr	Gr, Spongy	Sb, Gr	Sb, Gr	Ab, Sb, Gr	Ab, Sb, Gr	Ab, Sb – mainly in lower part, Gr	Ab, Sb, Gr
Porosity	15 – 20 %, common Chm, rare Chn, rare Sp., common Cdp.	20 – 30 %, rare Chm, common Chn, common Cdp.	15 – 20 %, common Chm, rare Chn, rare Cdp.	15 – 20 %, rare Chm, common Chn, common Cdp	15 – 20 %, common Chm, rare Chn, rare Sp.	20 – 30 %, rare Chm, common Chn, common Cdp.	15 – 20 %, common Chm, rare Chn, rare Cdp.	20 – 30 %, rare Chm, common Chn, common Cdp.
Sorting	unsorted	moderately sorted	moderately sorted	moderately sorted	unsorted	unsorted	unsorted	unsorted
Grain size	clay loam with high amount of debris; C/F(1mm) = 95:5; C/F (50μm) = 30:70	silty loam with presence of debris; C/F(1mm) = 50:50; C/F(50μm) = 60:40	silty loam with high amount of debris; C/F(1mm) = 50:40; C/F(50μm) = 20:80.	silty loam with presence of common debris; C/F(1mm) = 50:50; C/F(50μm) = 30:70.	silty loam with presence of debris; C/F(1mm) = 40:60; C/F(50μm) = 20:80.	clay loam with presence of debris; C/F(1mm) = 50:50; C/F(50μm) = 60:40.	silty loam with debris; C/F(1mm) = 90:10; C/F(50μm) = 30:70.	silty loam with presence of debris; C/F(1mm) = 50:50; C/F(50μm) = 30:70.
Coarse fraction	subangular Qu, Ptg, weathered Mi, Ser, Op; weathered Rf with Fe rich rims.	subangular Qu, Pl, weathered Mi; Ser, opaque minerals; partly weathered Rf with rare presence of Fe rims.	subangular Qu, Pl, brown Bt, orth-Pyr, weathered Mi, Ser, Op; weathered Rf with presence Fe rich rims.	subangular Qu, Pl, weathered Mi; Ser, Op; brown Bt, orth-Pyr, marble, partly weathered Rf with rare presence of Fe rims.	subangular Qu, Pl, weathered Mi, Bt, orthPyr, Ser, Op; weathered Rf with Fe rich rims.	subangular Qu, Bt, diopside, Ptg, mica; Ser, Op; weathered Rf.	subangular Qu, Pl, weathered Mi, Ser, Op; weathered Rf with Fe rich rims.	subangular Qu, Pl, weathered Mi; Ser, Op; partly weathered Rf with rare presence of Fe rims.
Matrix	Dark brown to orange brown phosphatic, Cr Bf, close Po.	Brown, locally orange brown, Cr Bf, open Po.	Dark brown, grey to orange brown, Cr Bf, Po.	dark brown to orange brown, Cr Bf, Po.	Dark brown to orange brown phosphatic, Cr Bf, Po.	Gray, orange brown, Cr Bf, Po.	Very dark brown to orange brown phosphatic, Cr Bf, Po.	Brown, locally orange brown, Cr Bf, Po.
Organic matter	decomposed brown OM – rare, locally present; decomposed and partly decomposed roots – present; microcharcoal - rare; fragments of fungi nests and phytoliths - rare.	decomposed brown OM – rare; decomposed and partly decomposed roots – common; microcharcoal – present, locally common; fragments of fungi nests and phytoliths - rare.	decomposed brown OM – rare; decomposed and partly decomposed roots – rare; microcharcoal - present; fragments of fungi nests – rare; phytoliths - present.	decomposed brown OM – present, locally common; decomposed and partly decomposed roots – common; microcharcoal – rare, locally present; fragments of fungi nests and phytoliths – rare.	decomposed brown OM – common; decomposed and partly decomposed roots – present; microcharcoal - present; fragments of fungi nests rare, phytoliths - present.	decomposed brown OM – present; decomposed and partly decomposed roots – rare; microcharcoal - common; fragments of fungi nests – rare; phytoliths - present.	decomposed brown OM – common; decomposed and partly decomposed roots – present; microcharcoal - present; fragments of fungi nests – rare; phytoliths - present.	decomposed brown OM – rare, decomposed and partly decomposed roots – rare; microcharcoal - present; fragments of fungi nests and phytoliths - rare.
Pedo features	Fe rims on clasts – common; passage features - present; P neoformation – present.	Fe rims on clasts – rare; passage features - present; P neoformation – absent; depletion present.	Fe rims on clasts – common; passage features - rare; P neoformation – present.	Fe rims on clasts – rare; passage features - present; P neoformation – absent; depletion present.	Fe rims on clasts – present; passage features - rare; P neoformation – present.	decomposed brown OM – rare, decomposed and partly decomposed roots – rare; microcharcoal - present; fragments of fungi nests and phytoliths - rare.	Fe rims on clasts – rare; passage features - present; P neoformation – rare; depletion present.	Fe rims on clasts – rare; passage features - present; P neoformation – absent; depletion present.
Notes	Size of prevailing granulae is 200 – 300 μm in size; the ratio between the granulae and larger aggregates is 70: 30	Size of prevailing granulae is 40 – 80 μm in size; the ratio between the granulae and larger aggregates is 10: 90.	Size of prevailing granulae is 50 – 150 μm in size; the ratio between the granulae and larger aggregates is 20: 80.	Size of prevailing granulae is 40 – 80 μm in size; the ratio between the granulae and larger aggregates is 90: 10.	Size of prevailing granulae is 50 – 200 μm in size; the ratio between the granulae and larger aggregates is 30: 70.	Size of prevailing granulae is 80 – 200 μm in size; the ratio between the granulae and larger aggregates is 30: 70.	Size of prevailing granulae is 30 – 80 μm in size; the ratio between the granulae and larger aggregates is 70: 30.	Size of prevailing granulae is 30 – 80 μm in size; the ratio between the granulae and larger aggregates is 80: 20.

La Terrasse

La Terrasse - one of the higher parts of Mont Beuvray (815 m a. s. l.) is a plateau with an area of cca 1 ha (120 × 85 m), enclosed by embankments with ditches. La Terrasse itself has always attracted attention of researchers: firstly, it was expected to be the location of a citadelle (Garenne, 1867), Camp of Mark Antony (Bulliot, 1899). It was reinvestigated again in the 1980s "to look for the possible location of a Gallic cult" (Gruel and Beck, 1996). Trenches were open between 1986 and 1995 (Figure. 2), cutting through the enclosed space, the bank and the ditch resulting in a finding that the space was devoid of constructions and only a small number of artefacts were recovered, mostly from 1st century BCE (pottery and amphorae fragments, tegulae, an iron ring, a nail). Prehistoric pottery fragments (probably Neolithic/Bronze age) and chipped stone industry were repeatedly reported from the site (Gruel and Beck, 1986).

Methodology

Archaeological excavations

The area of La Terrasse was chosen for an investigation of a non-built-up area in the oppidum. To minimize the disturbance to the layers in place, four trenches excavated at La Terrasse in the years 1986/ 1987 and 1993 (cf. Gruel and Beck, 1996, Figure. 2) were reopened in 2019. Three of them were placed in the inside part of La Terrasse, one has also cut the bank/rampart (Figure. 2) on one side and another on the other side of the study area. The trench sections were cleaned, re-documented and the location of the 8 test-pits (1x1 m) – labeled A, to H – were chosen for multiproxy studies. In each newly excavated test-pit we excavated and sampled using 10 cm thick artificial units (while respecting the natural layers). Pottery and amphorae were classified (Table. 1) and dated based on the established chronology of ceramic finds from this oppidum (Paunier et al., 1994; Paunier and Luginbühl, 2004).

Sedimentology and micromorphology

A basic sedimentological description following standard field criteria is one of the key procedures in starting geoarchaeological research. It is based on parameters such as color, texture, and internal organization (Figure. 3) and also includes a micromorphological description (Table.

2). The color of sediments was identified in both wet and dry state using a Munsell soil color chart. The sampled 8 blocks of soil were placed in gypsum plaster. Due to the frequent occurrence of large clasts, relatively large blocks (15 × 10 cm) had to be collected. These samples were then slowly dried and impregnated by resin mixed with acetone in a vacuum chamber. After curing for six weeks, smaller samples were cut off from the blocks and thin-sectioned separately. The thin sections were prepared at the Terrascope laboratory in Troyes (France). The dimensions of the thin sections are approximately 10 × 7 cm. The basic micromorphological descriptions and interpretations are based on Stoops (2003), Stoops et al. (2010). Detailed descriptions and results of individual samples are described in the Table. 2.

The intensity of human impact and pedological processes, and the types of formation processes were not clear macroscopically so we employed three different techniques to determine the geochemical composition. Each technique provides different information about the substrate. The Energy Dispersive X-ray Fluorescence - ED-XRF (pXRF) was employed to provide first, prospective, general results about the geochemical composition of all sampled sections of the documented test pits i.e., sections A, B, D, E, G and H. The main advantage of this analytical technique is the high throughput, generation of statistically large set of the data allowing comparability between the sections and possibility of field measurements. The more time-consuming, but also more precise results in terms of the number of detected elements were produced/obtained by ICP EOS (applied only to three sections T1A, T1B and T1E) using Mehlich III extraction. Additionally, the measurement of total organic carbon (TOC), total nitrogen (TN), total suphur (TS) and N/ C proxies as a third geochemical approach was applied on samples from sections T1A, T1B and T1E. What are the differences between the applied geochemical approaches for the given proxies? The portable ED-XRF (pXRF) analyzer Delta Professional (Olympus InnovX) was operated in the Soil Geochem measurement mode. The samples in excavated pits were irradiated with two beams for one minute – 30 s of the 10-kV beam and 30 s of the 40-kV beam. Each sample was tested three times; the final value is the arithmetic average of the three measurements. The pXRF measures almost all of the elements in the sediment, it is relatively quick and low-cost, and also detects heavy element concentrations. Quality control was provided by the BAS Rudice Ltd. Company (https://www.bas.cz/) on 55 reference materials (e.g., SRM 2709a, 2710a, 2711a, OREAS 161, 164, 166, RTC 405, 408). For XRF spectrometry applications, (see Kalnicky and Singhvi, 2001; Hürkamp et al., 2009; Hall et al., 2014; Canti and

Huisman, 2015; Šmejda et al., 2017; Salisbury, 2020). The important information about the intensity of chemical weathering was obtained from the ratios of the Rb/Sr (see Figure. Geoch 1) (Gallet et al., 1996; Chen et al., 1999; Bloemendal et al., 2008), less significant information than from the Rb/K ratio (Zech et al., 2008) (see supplement). The geochemical composition was also assessed by a standardized Mehlich III. extraction procedure (Pansu and Gautheyrou, 2006). This extraction is suitable for detection of elements in the soil taken up by plants, which means that the final results may be quite different from the ED-XRF results. Extracted amounts of macroelements (Al, Ca, Fe, K, Mg, Mn, Na, P, S) as well as selected heavy metals (Cu, Zn, Pb, Cr) and As were quantified by the ICP EOS. Mehlich III extraction was also chosen to distinguish the loosely bound heavy metals fraction in the profiles and to get the CEC (cation exchange capacity) value. Information about human impact on the soil and the soil activity can be gleaned from the total organic carbon (TOC), total nitrogen (TN) and total sulfur (TS) results especially when combined with magnetic proxies (Lisá et al., 2012). Samples were measured using high-temperature combustion analyzer Vario Macro cube (Elementar, Germany), analyzing simultaneously C, H, N, S content. Samples were introduced in tin containers wrapped around the solid, together with the addition of tungstic oxide. Temperature parameters were set to 1125 ◦C for combustion and the copper-reductive workup processes took place at 850 ◦C. Soil cation exchange capacity (CEC) which showed to be crucial proxy for the recognoscation of buried horizons is an important physical and chemical proxy, which reflects not only the surface properties of soil colloids, but also the retention and supply capacity of soil fertilizer. The cation exchange capacity (CEC) of a soil is a measure of the quantity of negatively charged sites on soil surfaces that can retain positively charged ions (cations) such as calcium (Ca^{2+}), magnesium (Mg^{2+}), and potassium (K^+), by electrostatic forces Franzini et al. (1975). Cations retained electrostatically are easily exchangeable with cations in the soil solution so a soil with a higher CEC has a greater capacity to maintain adequate quantities of Ca^{2+}, Mg^{2+} and K^+ than a soil with a low CEC. A soil with a higher CEC may not necessarily be more fertile because a soil's CEC can also be occupied by acid cations such as hydrogen (H^+) and aluminum (Al^{3+}). CEC is calculated as CEC = Σ $Ca^{2+}+Mg^{2+}+K^{+}+Na^{+}+H^{+}+Al^{3+}$ ($cmol^+/kg$).

Table. 3. Laboratory code of investigated OSL sample, sample name, sample depth (m b. s. = meters below surface), specific activities of natural radionuclides, dose rate, estimated water content, number of measured aliquots, final equivalent dose (CAM model) and calculated age.

Lab Code	Sample name	Sampling depth (m.b.s.)	Th (Bq/kg)	U (Bq/kg)	K (Bq/kg)	Dose rate (Gy/Ka)	Water content (%)	Number of measured aliquots	Equivalent dose (Gy)	OSL Age (Ka)
GdTL-3556	Bibracte	0.48	110.1±4.3	85.5±3.1	1516±130	7.78±0.38	15±5	18	1135±0.39	1.39±0.09

Plant macroremains

For plant macro-remains (and other ecofacts like seeds, charcoal, faunal remains, etc.) deposit samples with volume between 5 and 10 L were collected from each excavated unit, a 10 cm mechanical spit. For this study 26 samples from trenches A, B, D, E and H were collected, originating from the depths of 30 cm below surface to the bottom of each test-pit. The samples from the surface (litter) and the first two upper layers were heavily disturbed by modern activities, so they were excluded from the analyses. To secure recovery of all ecofacts (seeds, charcoal, faunal remains, etc.) and artefacts, the deposit samples were processed using a combination of flotation, wash-over and wet-sieving methods (for details see Golánová and Malý, 2017). The dried flot fractions were sorted and the plant remains were studied using a stereomicroscope (Leica M80 at max 50 ×). Taxa identification was based on the available literature and modern and archaeological reference collections. For charcoal, the refractive surfaces of fragments larger than 2 mm were analyzed under a microscope with reflected light (Olympus BX 51 at max 200×). Detailed descriptions and per sample results for seeds and charcoal are available elsewhere (Hajnalová see Bibracte Report 2020 in print). Here we evaluate the seeds and charcoal counts and volume of roots of modern plants after collating the samples to the wider stratigraphic units corresponding to the main deposition events.

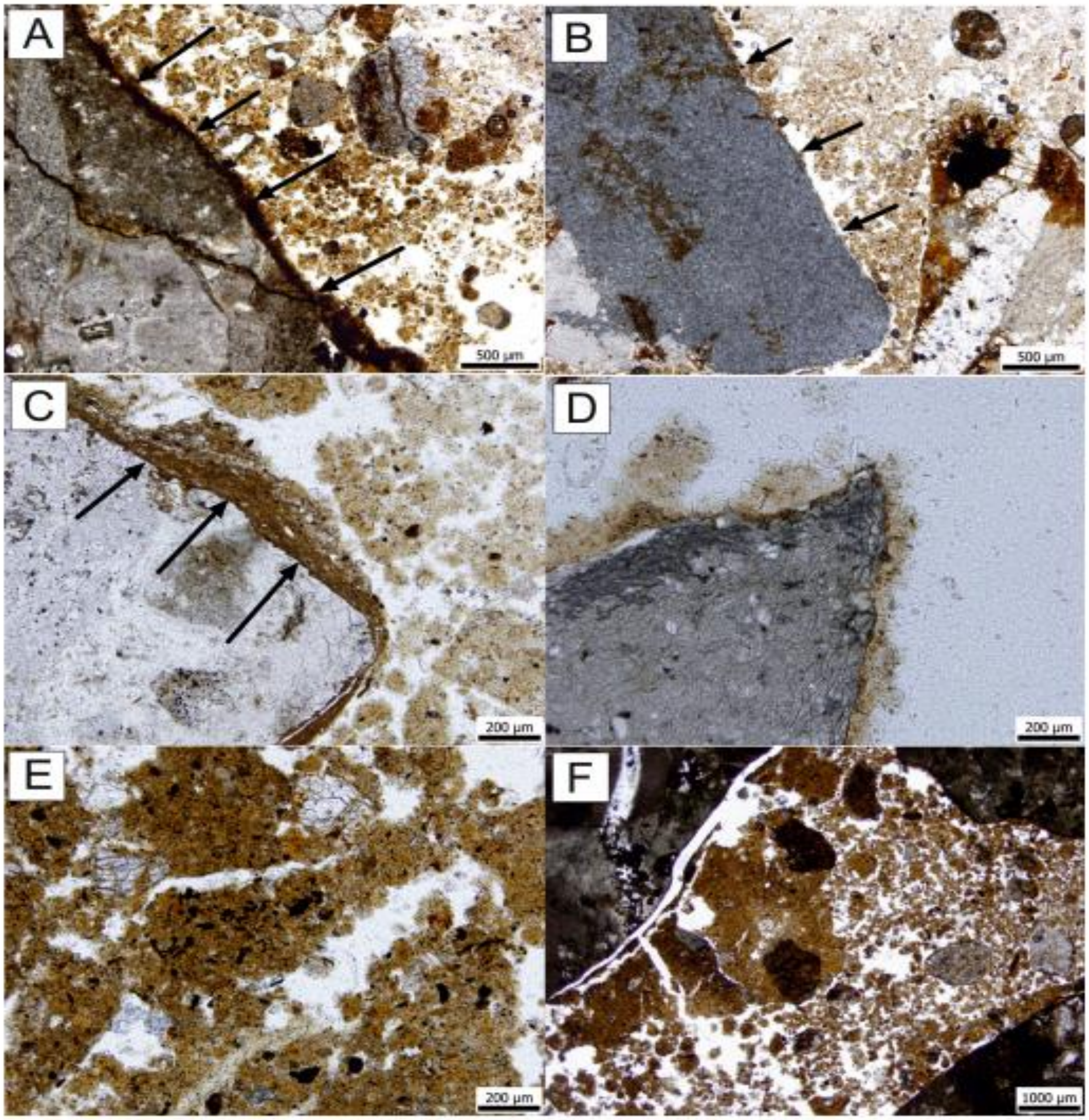

Figure. 4. Micromohological photodocumentation of choosen features; A - well developed Fe rims in sample TA1 (PPL – plane polarised light); B – clasts without Fe rims in sample TA2 (PPL); C – multilayered dirty silty coating in sample TE1 (PPL); D – phospatic neoformations coating clast surface in sample TB1; E – rather phosphatic matrix with microcharcoal and decomposed brown organic matter (PPL); F – soil aggregates of different sizes in sample TB1 (PPL).

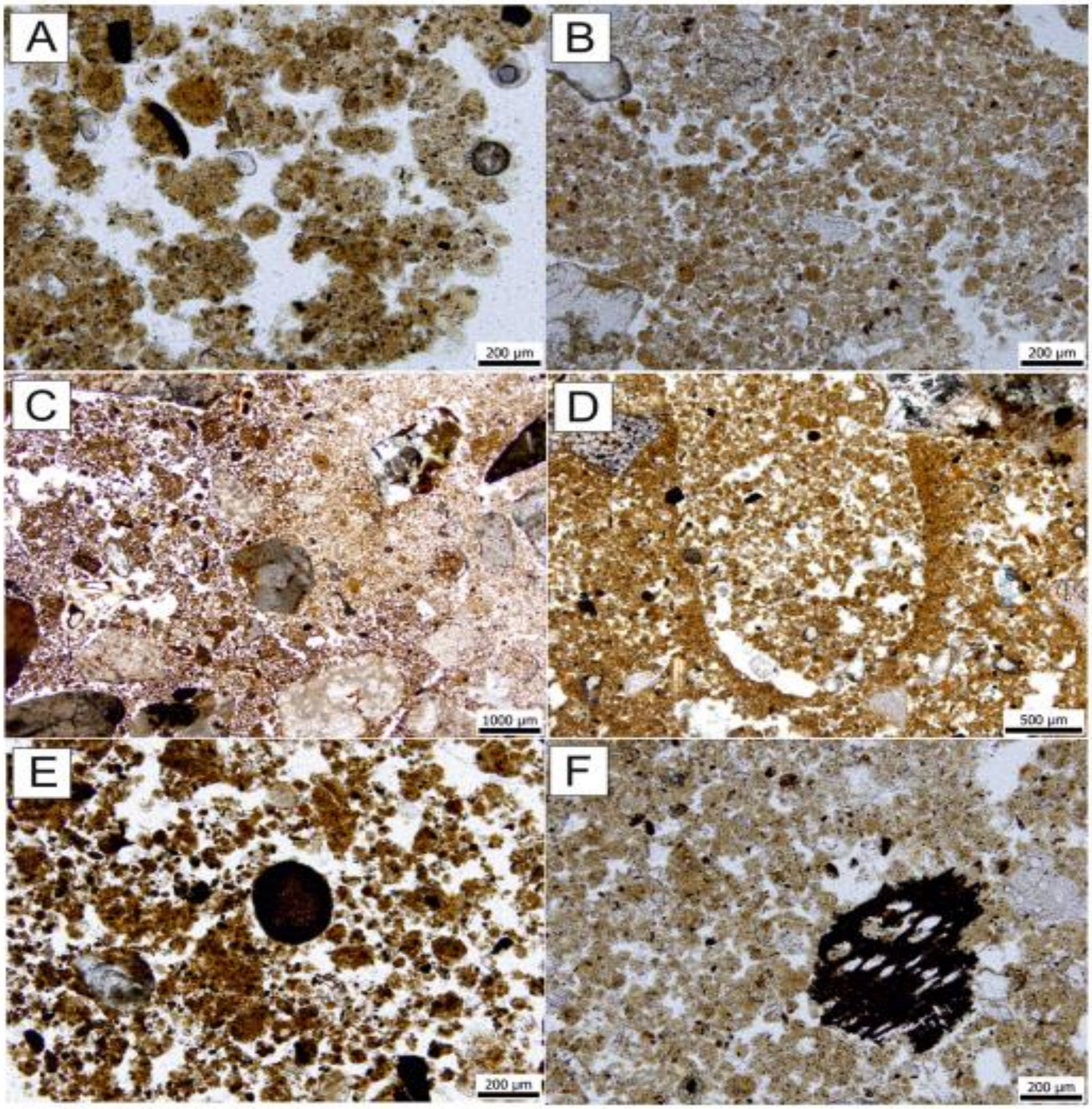

Figure. 5. Micromohological photodocumentation of choosen features; A – average size of granulaes in sample TA1 is 200 – 300 µm (PPL); B - average size of granulaes in sample TA2 is 40 – 80 µm (PPL); C - the matrix with the same size of granulae may differ in colour, i. e. in the amount of organic matter, Fe and P mainly - in sample TB2 (PPL); D – example of well-developed passage features in sample TA2 (PPL); E – example of the fungi nest located in phosphatic and organic matter rich granular microstructure of sample TE2 (PPL); F - example of a relatively larger microcharcoal fragment located in depleted light granular microstructure of sample TH (PPL).

OSL dating

The measurement has been carried out in the Gliwice luminescence dating laboratory (Moska et al., 2021). For dose rate determination high-resolution gamma spectrometry using a HPGe detector manufactured in Canberra was used in order to determine the content of U, Th and K in the sample. Prior to measurement, the sample was stored for about 3 weeks to ensure equilibrium between gaseous 222Rn and 226Ra in the 238U decay chain. Each measurement lasted for at least 24 h. The activities of the isotopes present in the sediment were determined using IAEA standards RGU, RGTh, RGK after subtraction of the detector background. Dose rates were calculated using the conversion factors of Guerin et al. (2011). For beta dose rate the cosmic ray dose-rate of the site was determined as described by Prescott and Stephan (1982). We assumed that the average water content was (15 ± 5) %. For further calculations a mean kα-value of 0.04 for silt-sized quartz (Rees-Jones, 1995a,b) was used. All necessary data for dose rate calculations are presented in Table. 3. For OSL measurements, medium grains of quartz (45–63 μm) were extracted from the sediment samples by routine treatment with 20% hydrochloric acid (HCl) and 20% hydrogen peroxide (H_2O_2) (Aitken, 1998). The quartz grains were separated using density separation with the application of sodium polytungstate solutions leaving grains of densities between 2.62 g/cm^3 and 2.75 g/cm^3. The grains were sieved, before etching with concentrated hydrofluoric acid (HF, 40 min). All OSL measurements were made using an automated Risø TL/OSL DA-20 reader used for the OSL of multi-grain aliquots, each of ca. 1 mg. The stimulation light source was a blue (470 ± 30 nm) light emitting diode (LED) array delivering 50 mW/cm^2 at the sample (Bøtter-Jensen et al., 2000). Detection was through 7.5 mm of Hoya U-340 filter. Equivalent doses were determined using the single-aliquot regenerative dose (SAR) protocol (Murray and Wintle, 2000). The final result was calculated using Central Age Model (CAM) (Galbraith et al., 1999) and the equivalent dose distributions (Berger, 2010) were counted. Obtained overdispersion is about 15%.

Results and interpretations

Archaeological findings

The number of finds documented in previous excavations from 1986/1987 and 1993 is very low (cf. Gruel and Beck 1996, Figure. 2), which was confirmed by finds from the 8 test-pits in 2019. The artefacts– mainly strongly fragmented and worn pottery (112 pc), amphorae (49 pc) and ceramic building material (29 pc) were found together with iron fragments (9 pc) and chipped stone artefacts (6 pc). The ceramics were reduced to tiny fragments (total 2.733 g), with a median weight of 1.85 g (the average weight of 17.9 g is due to a small number of large pieces). However, as many as 32 sherds out of the total of 196 weigh only 0.1 g, 56 sherds weigh less than 1 g. This is unusual as the excavation at Bibracte typically produce tens of kilograms of relatively well-preserved pottery (Golánová et al., 2015). Stratigraphically, the artefacts are mixed (chipped stone artefacts were recovered from the same layers as pottery and 1st century BCE amphorae). This indicates a high degree of bioturbation, or human impact during the formation of the sedimentary deposit. Despite the presence of suitable flat terrain, no traces of structures except for the surrounding ramparts and ditches were found in the area of La Terrasse. The central part of La Terrasse documented in test-pits A, B, C is characterized by the presence of ceramic fragments to a depth of 40 cm below the surface, so not reaching the "buried soil horizon" at 50 – 60 cm (see Figure. 4 – figure with sedimentary layers). In test-pits D and E, which already follow the slope of the subsoil towards the ramparts, there are individual sherds as deep as 50 cm (in the test-pit D) and 80 cm (in the test-pit E) – cf (Table. 1). The situation in test-pit F, which cuts the inner part of the rampart itself, is different: the sherds were scattered in all layers of the earthwork (including the base of the rampart) down to a depth of 140 cm, containing a mixture of artefacts including Iron Age pottery (possibly from the 1st century BCE though an earlier date cannot be excluded in any of the cases), but also well represented prehistoric (Bronze or Early Iron Age) pottery and one chipped stone artefact. Stone artefacts were also found mixed with 1st century BCE pottery in other test-pits (Table. 1). In test-pit H, which is situated on the opposite side of La Terrasse in descending terrain next to the rampart, numerous sherds were detected at a depth of 70–80 cm.

Sedimentology and micromorphology

Differences in sediments across the site are relatively minor (Figure. 3). The thickness of the material sitting on the frost weathered in situ geological substrate ranges between 55 and 60 cm in the central part of La Terrasse and 80 – 120 cm in the areas close to the rampart. The important fact is that the geological in situ weathered substrate descends towards the rampart where test-pits E and H were located. Those sections are therefore deeper. The fill of studied layers was pedologically divided into 4 main layers (see Figure. 3). Generally, the uppermost layer is composed of and partly decomposed organic matter on the very surface and A horizon (Figures. 4 and 5 – micromorphology; marked as I. in Figure. 3). It is represented by unsorted sandy silts with the presence of clasts of 1 – 2 cm (50 %). This layer is heavily bioturbated by roots and micro and mesofauna and its thickness ranges between 15 and 30 cm); average color 10YR 3/3. The transitions between layer I. and II. is clear. Towards the deep parts of the sections the second layer of unsorted sandy silts containing clasts 1 – 5 cm (50 %) and color 10YR 5/3 appears. It is marked as II. in Figure. 3. This layer has an average thickness of 20 – 40 cm and it has signs of root bioturbation. The transitions between layer II. and III. is abrupt. An approximately 10 cm thick third layer of unsorted sandy silts with the color 10YR 4/4 appears in most of the studied sections but was not easily identifiable, mainly in the central part of the studied area. It was easier to determine several days after the trenches were reopened. The thickness of this layer increase toward the ramparts, so its thickness is 20 cm in the section D and 50 cm in the section E. The transitions between layer III. and IV. is clear to abrupt. The following (fourth) layer consisted of weathered geological substrate. This sediment possessed low porosity, sandy silt grain size and clasts 1–2 cm and bigger (80 %). The color of the frost weathered geological substrate is 10YR 6/4. all described layers are abrupt (with the exception of the fourth). The main distinguishing features between the individual micromorphological samples (Table. 2) were found to be the intensity of development (Figure. 4A) and the absence (Figure. 4B) of Fe rims on clasts. Only in the case of one sample was a well-developed and common dirty silty coating identified (Figure. 4C).

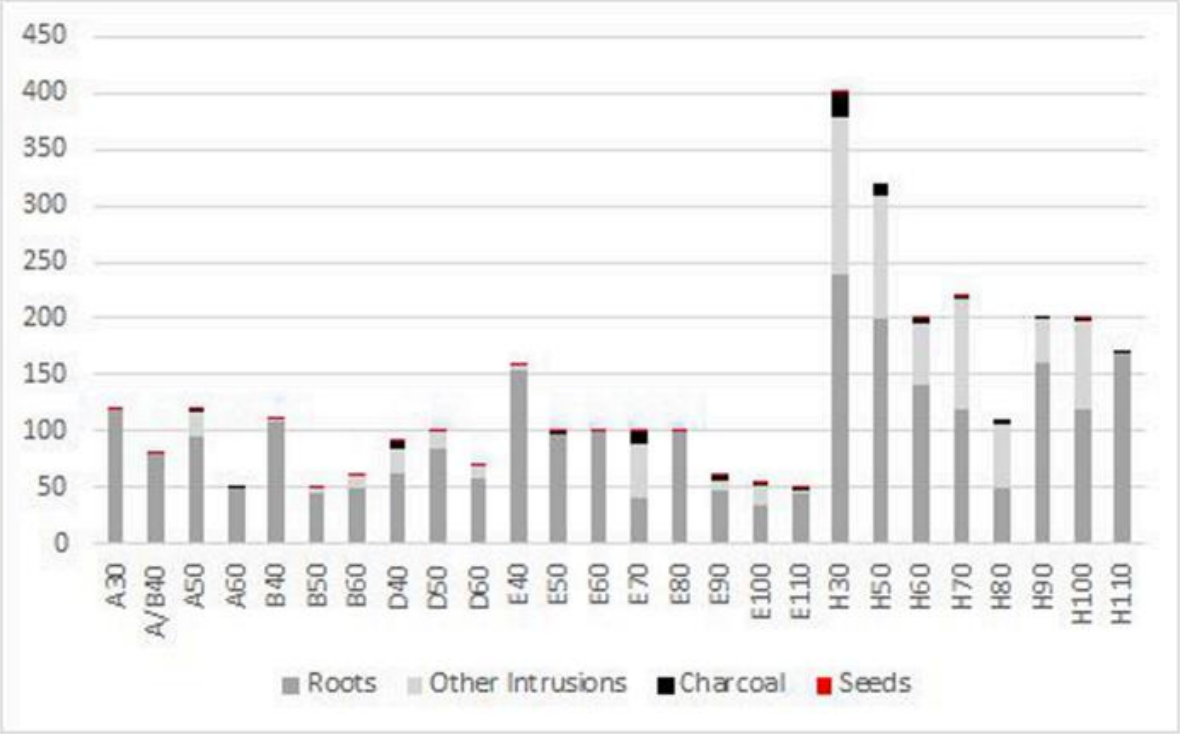

Figure. 6. Bibracte, La Terrasse. Volume (ml) of potentially macroremain (wood charcoal, seeds) and intrusive (roots and other) finds in floated fractions of deposit samples. Category „other intrusions” include floating undissolved sediment, decaying organic litter (leaves, tree bark, mosses), insect remains, etc.

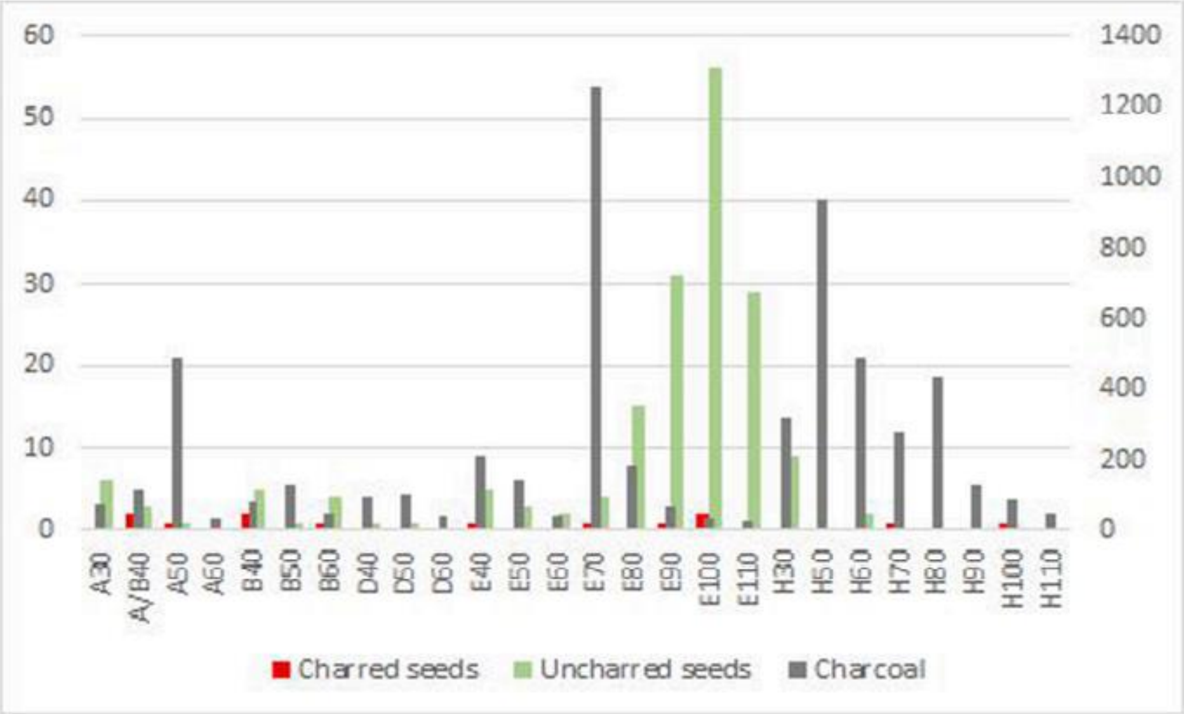

Figure. 7. Bibracte, La Terrasse. Number of individual species (NISP) of charcoal fragments (left axis) and charred and uncharred seeds (right axis).

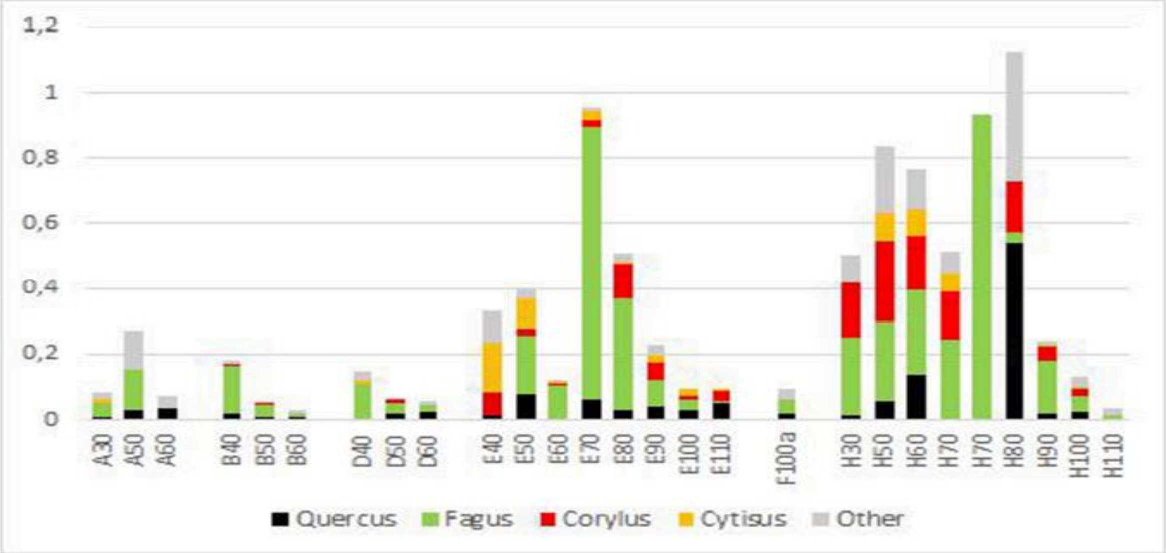

Figure. 8. Bibracte, La Terrasse. Weight (g) of main and other wood taxa in individual samples.

the presence (Figure. 4D) or absence of phosphatic neoformations and the color of the matrix depending on the phosphorus content (Figure. 4E). The third basic distinguishing feature is

(Figure. 3) the structure of the matrix itself. In the case of a buried soil surface, the presence of larger subangular soil aggregates is always significant at the expense of granulae (Figure. 4F). At the same time, the granules in the buried soil horizons are larger (Figure. 5A) than in the overburden (Figure. 5B). The color of the matrix, depending on the content of the organic matter, Fe and P, is often locally variable (Figure. 5C). The intensity of the coloration may also depend on the depletion, which is more pronounced in the overburden (Figure. 5B; 5F). Bioturbation (Figure. 5D) is not a significant distinguishing element and occurs intensely is both buried soil and overburden. Fungi nests (Figure. 5E) and microcharcoal (Figure. 5F) occur with great variability across studied profiles.

Geochemistry, grain size and magnetic properties

The geochemical results obtained with the portable ED-XRF (pXRF) analyzer show that the concentrations of measured elements are quite constant and the differences in the content of some elements can mostly be attributed to the uppermost soil layer, the frost weathered geological substrate, or to the layer directly above that substrate. The most significant change is the increase of Mn, Fe, K, P, S, Pb and Zn in the upper ten cm of the soil (see supplementary data). This increase is linked to the high bioturbation and the accumulation of organic matter (see Figure. 3) which binds the heavy elements. In contrast, the frost weathered geological substrate contains greater concentrations of Si, K, Zn, Zr, Pb and Ti, i. e., minerals typical for the in situ geological substrate of this area. The layer directly above the frost weathered geological substrate is quite variable across, but generally richer in elements such as Cu, Zn, S, Mn, P, Fe and Al. Because the amount of organic matter is low in this layer (Figure. 3), we can propose that the increase of those elements is linked to the presence of ashy materials. The ash crystals were not recorded because they didńt preserved in open space environment, but presence of microcharcoal was recoded repeatedly there in thin sections. The ICP-EOS results from the Mehlich III extraction shows relatively low and constant geochemical values, with relatively different trends compared to the ED-XRF results (see supplement). There are exceptions of slightly higher values for concentrations of Ca, Mg, K and Na directly above the weathered in situ substrate as well as in recent A horizon. This is well expressed by Ca/Mg ratio (Figure. 3) which corresponds to the increased amount of TOC. Section D close to the rampart has a layer III with increased values of Ca, Mg, K and Na which is thicker than in the other sections (see supplementary data). High concentrations of Cu, Zn and Pb (but not As) were also detected. The concentrations of these elements vary throughout the study area and the concentrations are greater than the background concentrations in the geological substrate (see supplementary data). Interesting results were brought also by the Rb/Sr ratio (see supplementary data). Greater intensity of leaching was clearly detected in sections D, E and G, i.e., sections close to the ramparts contrary to the sections A, B and H located in the central parts of the study area. Interesting result were brought by effective CEC. This proxy increases in two positions in every studied section (Figure. 3). The first one corresponds to the layer II, i.e., the position of B horizon of recent soil. The second one corresponds to the lower part of the layer III. and the uppermost part of the layer IV. and might be related of B horizon of former soil which survived only as relicts. The uppermost parts of the studied sections (upper 30 cm) produce the highest TOC, TN and TS values (see Figure. 3). There is a good correlation between TOC and Mg/Ca ratio (Figure. 3). The rest of the studied material has more or less constant low values and there is a visible gradual decrease of these values towards the deeper parts of the sections. A visible stagnation in these values is evident at depths 50 – 60 cm in sections TA and TD and at depths 70 – 120 cm in section E. The lowermost parts of the studied sections possess the lowest detected values. The C/N ratio which generally reflects the soil bacterial activity is very high and does not show any significant trends. The grain size distribution within the study sections is variable and does not show any significant trends corresponding to the long term pedological transformations, human influence, or change in provenience (see Figure. 3 for clay and supplementary data). The silty fraction prevails and only few samples possess a sandy fraction. Most of the measured samples show an upward trend in the amount of coarse fraction except for samples from section TA at a depth of 60 – 70 cm, T3D at depths 0 – 10 cm and T3D at depth 30 – 40 cm. Sandy fraction was detected in only these three samples. This is possibly the result of bioturbation reflecting the different material provenance or post depositional changes. The amount of clay fraction shows only low correlation with CEC (Figure. 3). The values of magnetic susceptibility as a proxy for grain size distribution (see supplementary data) are quite variable in all studied sections and in this case clearly do not depend on grain size distribution. The most enhanced susceptibility was documented in the lowermost parts of section E (90– 110 cm below the surface) close to the rampart, at a depth of 40–50 cm of section G, also close to the rampart at the opposite side of the studied area and also (relatively) in the upper parts of section A in the center of the study area (see supplementary data).

In the single sections, the lowermost values of magnetic susceptibility were usually (but not always) detected at the very bottom of the sections in the cryoturbated geological substrate (see supplementary data).

Archaeobotany

The La Terrasse sedimentary archives appear to be heavily bioturbated by roots of woody plants. Although the volume of roots (present in dried flot fractions) generally decreases towards the deeper strata (in all but test-pit H), there are exceptions to this rule (Figure. 6). The root accumulations in lower strata probably coincide with buried fossil soil horizon(s). Other types of plant macroremains, such as wood charcoal, seeds and fruits fossilized (archaeologized) through charring or seeds fossilized through mineralization, are extremely rare (Figure. 7). The charcoal assemblage consists of over 5800 fragments, but as individual fragments rarely exceed 2 mm in size, the total weight is very low (23.0641 g). It was possible to taxonomically determine only 839 fragments (8.857 g). It is noteworthy that such a small amount of charcoal is not consistent with the amount of charcoal detected in settled or built-up areas of the Bibracte oppidum, where these are much more numerous and much larger in sizes (Bellavia, 2013; 2014; 2015). Beech (Fagus sylvatica) and oak (Quercus) charcoal are the most common types and occur in each sample Figure. 8. Beech dominates almost all of the samples, though in lower layers (A60, D50, D60, E100, E110 and H80) there is a higher (30% to 80 %) proportion of oak. Other two common taxa are hazel (Corylus avellana, absent in 7 samples) and common broom (Cytisus cf. scoparius, absent in 6 samples). Hazel and broom are present in higher proportions (between 10 and 30 %) in samples from upper (A30, A40, D40, E40) or middle parts of the individual profiles (D50, E50, H30, H50, H60, H70). The remaining twelve species (Prunus, Castanea/Quercus, Pomoidae, Betula, Fraxinus, Betula, Tilia, Alnus, Acer, Populus/Salix, Populus, Betula/Alnus, Indeterminate broad-leaved trees). They occur in less than half of the samples (Figure. 9). Alongside we find local (beech, oak, ash) and non-local taxa (willow, poplar, alder, lime) for the area of oppidum as well as trees from forests and open deforested stands. As the trenches are situated close to each other, the recorded variation suggests that at least some of the charcoal does not originate from burning vegetation in situ or comes from different time periods when the area had a different vegetation cover. For non-local trees like lime, willow/poplar, maple their wood was either transported from elsewhere and burned at the site, or the charcoal was brought in with the deposits moved there from elsewhere. Some of the taxa are not suitable as fuelwood, but are often used for manufacturing wooden objects, which supports the anthropogenic origin of the charcoal. The relatively low variation between taxa from different depths within individual test-pits and the presence of roots even in the lowermost samples, indicate possible transport and mixing of small charcoal fragments via bioturbation. Seeds and fruits are rare (Figure. 7). Charred seeds are much less numerous than in built-up areas of the Bibracte oppidum (Wiethold, 2011; Bonnaire, 2013; Wiethold, 2014;). Single cereal grains of millet (Panicum miliaceum) and barley (Hordeum vulgare) were recovered from the middle layers of A (40, 50) and H (70). Other finds include wild fruits – hazel, beech, raspberry (Rubus cf. idaeus) and one wild herb or weed (Galium sp.). While possible garden fruit, fragment of cereal straw and raspberry comes only from the lower layers (B60, E90, H100), hazel and beech, which can grow locally, were present in both the upper and the lower layers. Charred seeds concentrate mostly in the layer(s) just above the cryoturbated geological substrate in all but test-pit H, which may be evidence for the presence of a former cultural layer or surface. Uncharred seeds usually concentrate in the upper layers of soil profiles where they represent a natural seed-bank. It was therefore surprising to find fragments of uncharred shells and seeds of beech, hazel, blackberry, elderberry and broom (and a single acorn and Polygonum aviculare seed) all the way to the middle parts of the sequences. Most surprising was the presence of beech buds and a large number of elderberry seeds in samples from just above the weathered bedrock in section E (90, 100, 110). They were in the sample alongside charred shells of hazel, relatively numerous charcoal fragments and roots of modern plants. While elderberry seeds with seed-coats rich in minerals fossilize naturally and could be of ancient origin (similar to charred remains), the tree buds and roots indicate they moved via deep bioturbation. To conclude – the mode of preservation, distribution, numbers and recovered species of charred plant macroremains within the excavated sequences suggest: 1. low intensity of human exploitation in the area, due to the much lower appearance of the macroremains; 2. presence of possibly a remnant of a thin ancient cultural layer at the base of section E (70) 90 to 110 cm); 3. anthropogenic and non-local origin of at least some of the charcoal fragments; 4. (strong impact) vertical bioturbation processes within deposit sequences.

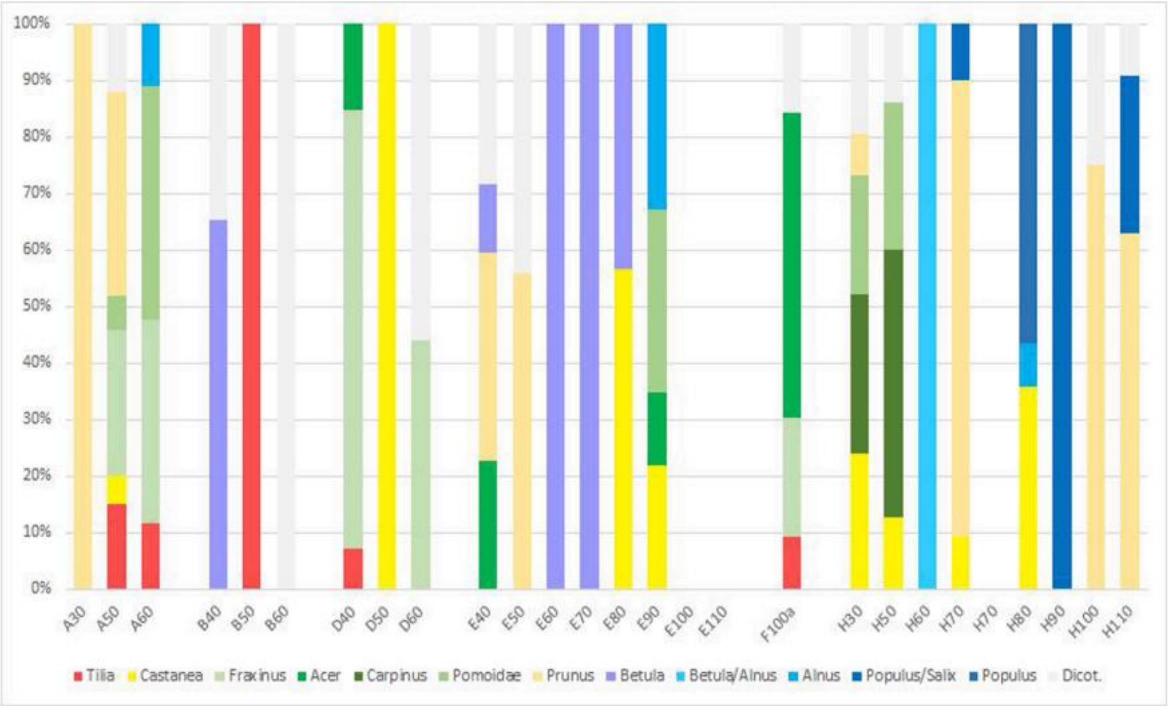

Figure. 9. Bibracte, La Terrasse. Proportions of "other" wood taxa in individual samples, based on WISP - weight of individual specimens (g).

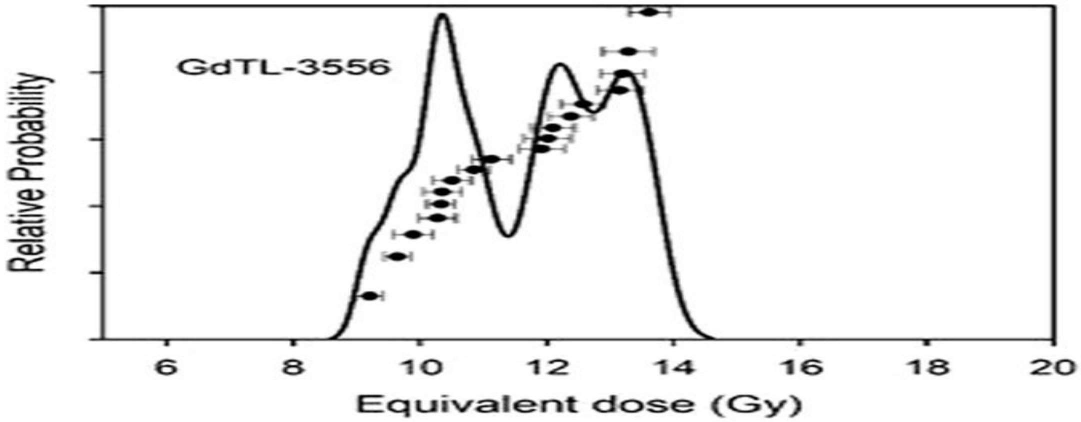

Figure. 10. OSL Graph of the equivalent dose distribution (Berger, 2010) for the investigated sample.

OSL dating

The obtained luminescence result of 1,39 ± 0,09 ka (i.e., 561 CE) is younger than expected (based on archeological descriptions). Equivalent dose distributions (Berger, 2010) presented in Figure. 10 and Table. 4 shows multimodality despite the fact that obtained over dispersion does not clearly suggest it. Such distributions often have over dispersion parameters ranging between 10 and 20 % so it is not possible to observe the typical unimodal shape of the distribution, however this does not change the fact that CAM for all aliquots remains suitable for estimation of the final value of the equivalent dose. Usually, fluvial samples are representative of this group and in this case some asymmetry in the distribution (i.e., lack of statistical significance) may be observed (Arnold et al., 2007). On the other hand, this kind of distribution can represent or be derived from the post-depositional disturbance of sedimentary deposits and soils mixed during the bioturbation process (Bateman et al., 2003).

Discussion

Are we able to detect the surface of La Terrasse in different phases of site occupation?

The main aim of this paper is a discussion of how to identify the occupational surface remnants at a heavily eroded site and to describe the origin and properties of newly formed archaeological soil. The occupational surface should be linked to a particular occupational timespan. In the case of Bibracte, where erosion processes (mainly sheet wash and those triggered by humans) took place repeatedly, it is quite difficult to state a precise limit for stabilization of the surface during different phases of occupation. We are dealing with the highest part of the oppidum, while on other similarly exposed parts of the oppidum the soil surface is minimal or protruding bed-rock of granitic rocks is exposed: Theurot de la Roche, Pierre de la Wivre etc. (Boyer, 1996; Boyer et al., 1996; Luginbühl et al., 2014, 170-174; Guichard et al., 2018, 175). At the same time, it is clear that at least 55 cm of unsorted material that lies on the eroded subsoil of La Terrasse must have been accumulated by humans, because there is no space above La Terrasse where the material could be deposited (eroded) from. The material accumulated by humans on the cryoturbated geological substrate of La Terrasse contains small fragments of artefacts related to different periods ranging from prehistory to Iron Age. The cryoturbation of the uppermost part of the geological substrate is well expressed by the stone orientation and was detected also micromorphologicaly from the matrix. The former surface situated between the frost weathered geological substrate and anthropogenically accumulated soil is in some cases very indistinct and can be highlighted macroscopically only as slightly different hues. The geochemical signal in combination with the magnetic susceptibility is more pronounced (accumulation of elements connected with the burning activities), but its intensity is not as high as in a typical cultural layer or soil maintained by humans (Šmejda et al., 2018; Janovský et al., 2020a,b). These geochemical proxies are not separately convincing, but may be used as a proof of human activities when they are read as a fold up mosaic of information, for example, by adding the information about the slightly greater number of artefacts and archaeobotanical findings (mainly section E and bottom of sections A, B and D) documenting the presence of possibly a remnant of very thin ancient cultural layer. But where is the former soil horizon developed since the beginning of Holocene up to the anthropogenic accumulation of overburden and how to identify it? The OSL date suggests that the former surface was exposed before 561 CE. If there would not be any erosion present than since the beginning of Holocene the well-developed soil should originate there. Macroscopically, the horizon between the cryoturbated geological substrate and anthropogenically accumulated mass of sediments could be identified as the spodic horizon, which usually has brownish black or reddish-brown color caused by the presence of an increased amount of organic mass (as opposed to overburden) as well as oxides and hydroxides Al and sometimes also Fe. The Al and Fe are present in relatively large amounts (see supplemental), but the differences between this horizon and the overburden are not very significant. The amount of CEC represents the presence of B horizon or the relicts of B horizons more effectively but still the intensity of the soil development doesńt correspond to the timespan expected since the beginning of Holocene. The chronosequence studies show that incipient podsolization usually becomes visible between 100 and 500 y and mature Podzols develop in 1,000–6,000 y and the time for its development depends mainly on the type of the vegetation (Sauer et al., 2007; Zwanzig et al., 2021). The explanation of absence of not well developed spodic horizon may be explained by the intensity of erosion processes and in fact the former surface is possible to detect by just slightly changed geochemical signal.

Geomorphology, climate and human impact as possible triggers of erosion processes

As already mentioned, La Terrasse is one of the highest areas of the Bibracte oppidum. Apart from the north-eastern part of La Terrasse, the relatively flat terrain of that area falls sharply into the valley (Figure. 1). Today, the steep rocky geological background is mitigated by the construction of the rampart, but before the construction of ramparts, the exposure of the terrain would have played a significant role in the degree of erosion intensification. The slope processes start generally since the 2 % of the slope. As mentioned in the chapter 2.2 the most of the Bibracte "intra murros" area is exposed in the angle higher than 7 % and it is obvious from the archaeological record that the area was intensively cut of vegetation. Liu et al. (2001) show that the critical slope gradient of soil erosion is dependent on grain size, soil bulk density, surface roughness, runoff length, net rain excess, and the friction coefficient of soil, etc. The critical slope gradient has been estimated theoretically with its range between 41.5◦ ∽ 50◦. Taking in account that the vegetation of the oppidum had been intensively cut off during the construction of it and the frost weathered geological substrate prone to erosion was exposed we can assume relatively high erosion which influenced intensively the recent soil cover. After the encircling rampart construction, the terrain/landscape was relatively stabilized/preserved and the natural or anthropogenic erosion processes ceased. The layer representing the former (now buried) surface, i.e., the remnants of the occupational layer at La Terrasse was documented as a thin layer, which contained the smallest number of finds in the highest central part of La Terrasse (see Figures. 2 and 3, the layer III.). Towards the rampart the thickness of that layer increases. This layer (at twice the original thickness) was also detected under the rampart. Neolithic chipped stone artefacts were recovered in the area of La Terrasse, but these were found in the overburden (A20, B20, C30, E80, F140, H50) and not buried below them except for the one from 80 cm depth in section E. Missing well-developed soil horizons between the cryogenically influenced geological substrate and the human induced overburden which was accumulated at La Terrasse after 561 CE are strong proofs of soil erosion at the place. We suppose, that the erosion processes preceding the Neolithic occupation were triggered mainly by climate, as no proof of pre-neolithic occupation was detected in the area and there are no signs of forest clearance (wood charcoal accumulations). During the erosion, almost all the soil, developed in the area since the beginning of Holocene until the onset of Neolithic, was removed and redeposited down the slopes. In spite of that is necessary to take into the account that the first human induced erosion in Europe occurred at the beginning of the Neolithic period (approximately 5500–2200 BCE). The sedimentological archives of the Massif Central indicate that human impact on the landscape begins in the 5th millennium BC (Surmely et al., 2009; Miras et al., 2011; Cubizolle et al., 2014; Dendievel et al., 2019). The second human induced phase of erosion in the area of Massif Central occurred from the Early Iron Age (ca. 7th–6th century BCE) (Allée, 2003; Arnaud et al., 2012; Notebaert and Berger, 2014; Notebaert et al., 2014; Mayoral, 2018). This continued until and throughout the La Tene period (5th century BCE–1st century CE; Mäckel et al., 2002; Mayoral et al., 2018) and peaked locally in the Gallo-Roman period (1st –5th century CE; Dendievel et al., 2019; Notebaert and Berger, 2014; Mäckel et al., 2002). It seems, that before the La Tene period the soils at Bibracte had to be already eroded, because redeposited soil was not detected in the area between the slope and ramparts which surrounds the site. With regards to human impact, the indicators of agro-pastoral activities are very scarce and punctuated throughout prehistory and the Bronze Age (from ca 5 000 to 800 BCE). The oldest traces of occupation of Mont Beuvray date back to the Neolithic period (5th millennium BC; Martineau et al., 2011; Guichard and Paris, 2013). Even after this date, and despite further deforestation phases occurring during the Iron Age (800–50 BC), the classical Middle Ages (around 1000 CE) and the Modern period, woodland remains dominant, and proximal pollen and fungal indicators of human activity are only present in one core, dating to the beginning of the 16th century to the beginning of the 19th century (Jouffroy-Bapicot et al., 2013). The decrease of anthropogenic pollen indicators during the middle Neolithic in some parts of the Morvan coincides with the onset of the Neoglacial, but this trend is not obvious everywhere (Jouffroy-Bapicot et al., 2013). The most obvious climatic change in the Morvan area is the decrease in human activity during the middle Bronze Age connected with a cool and moist phase corresponding to an abandonment of lacustrine habitats in the Jura and the Alps (Magny et al., 2009). The vegetation and land-use history of the surroundings of Mont Beuvray are documented by three palaeoecologically studied peat sequences (GrandMontarnu near the Haut-Folin, sources de l'Yonne and Port-desLamberts some 5 km north of Mont Beuvray; Jouffroy- Bapicot et al., 2013) and recently also by two sections in the alluvial zone of small streams close to Mont Beuvray (Petřík et al., 2021). Agro-pastoral indicators, woodland openness and metallic pollution increased in the Late Iron Age (since the 5th century BCE) and reached a maximum during the last two centuries BC (Jouffroy-Bapicot, 2007). This trend was also documented in the aggradation of alluvial deposits around Bibracte (Petřík et al., 2021). Thereafter, agro-pastoral activities in the Haut-Morvan decreased during the Gallo-Roman period, but increased again during the Early Medieval period (5th– 10th century CE). Palynological, archaeological and historical data complement each other, and document the history of the Medieval period and Modern Times (Balland et al., 2019). The study of alluvial deposits in close proximity of Bibracte show that increased sedimentary activity occurred in the High Medieval period and continued until the post-Medieval period (Petřík et al., 2021).

The increasing human impact during the Late Iron Age and the Roman period in the Morvan is in keeping with the central European trend, which coincides with a wetter and warmer climate (Büntgen et al., 2011). The impact of the 'Little Ice Age' on the Morvan Massif is not clear, probably mainly because of the specific land use prevalent on the massif at that time. The exploitation of firewood relegates agropastoral activities to a marginal activity (Jouffroy-Bapicot et al., 2013). The Medieval Climate optimum is reflected in the Morvan area by the intense cultivation of chestnut trees on its southern slopes (JouffroyBapicot et al., 2013). Favorable climate conditions may have facilitated this cultivation, which was at the periphery of the known geographic distribution of chestnut production during the late Middle Ages and modern times (Conedera et al., 2009).

The evidence of human impact in an area seemingly not influenced by human activity

The La Terrasse area is heavily anthropogenically influenced even though the corresponding archaeological soils do not suggest this. Disregarding the possible anthropogenically triggered erosion events before AD 561, two construction activities/phases at the site can be considered as the main anthropogenic influences. One of them is the construction of ramparts, which enclose this area from three sides and thus prevent possible erosion of the soil cover. The age of the ramparts is not sufficiently corroborated, but the terminus post quem Iron Age pottery, probably dates to the 1st century BCE (cf. also Almagro-Gorbea, 1989, 214) - this dating would be in agreement with the existence of a ditch, which formed part of the enclosure (Golánová et al., 2020, 2021); though an earlier Iron Age date for the rampart can't be excluded. In spite of the fact, that

OSL sample show the date younger than the construction of the rampart the coexistence of rampart construction and the accumulation of overburden can't be excluded. At first there exist just one date. The second reason is the unusually high dose rate (natural concentration of the radioisotopes more than two times higher than for typical colluvium or loess deposits), which may influence final younger age of the sample. Another construction activity/phase that took place in the studied area in the past is represented by surface thickening and/or levelling of the surface inside the ramparts by about 50 cm. The former surface on which the new layer was deposited is detectable only as a slight discoloration, but a geochemical signal indicates the presence of ashes, microcharcoal and increased amounts of corroded clasts. The main mass of accumulated sediments shows in the micromorphological record, and essentially no significant changes are expected for the uppermost 30 cm. There is very little evidence for the presence of cultural material. The accumulated material does not contain corroded clasts, but occasionally contains microcharcoal or decomposed organic matter. These elements are the result of possible anthropogenic contamination during the sediment deposition, or contamination due to the micro and mesofauna bioturbation/action. Mehlich III (Mehlich, 1984) extraction of all sections as well as XRF analyses revealed increased amounts of Cu, Pb and Zn, very unevenly distributed in the profiles. Metal amounts reach the level typical for anthropogenic origin, reflecting the production and/or a workshop in the area studied. Accessibility of the heavy metals at relatively mild Mehlich III (Mehlich, 1984) extraction conditions points to a weathered geological substrate, or to the soil potentially containing dissipated waste from smelting/metal workshop but not metals tightly bound in (sulfidic) ores. It should be mentioned that Cu and especially Pb are quite conservative in soil profiles (nonmobile), thus, it could be expected that the metals were introduced to the profiles through a longer lasting activity. It is a question if to link the increase of heavy elements such as Pb and Zn in the uppermost parts of the studied section with the increase in mining activity. We know, that the sedimentary archives of Bibracte show the strong impact of human activities, namely of paleometallurgy, on the natural environment (Cauuet and Tamas, 2008; Duval and Lacoste, 2014). The uppermost part of La Terrasse sedimentary sections is rich in Pb but on organic matter which bounds Pb as well. Jouffroy-Bapicot et al. (2008) documented the sediments rich of Pb in a peat bog cores near Bibracte and linked that record to the local mining operations starting from the Late Bronze Age, ca. cal. 1300BCE. They argue, that the lead inputs peaked at the height of Aeduan civilization and then decreased after the Roman conquest of Gaul, when the site was abandoned. Petřík et al. (2021) linked the peaks of Pb recognized in the alluvium around Bibracte with the mining activity as well, but in their case, due to the Pb values such trends are more easily explained by the effect of bonding (and accumulating) of these elements onto the organic matter. This is similar to La Terrasse, because the uppermost 30 cm manifests increased values of total carbon, total nitrogen and sulfur and thus corresponds to the presence of a relatively well-developed "A" horizon unaffected by erosion factors precisely due to the stabilization of the landscape (see above).

Conclusions

The most obvious anthropogenic influence on the La Terrasse relief/ area at present is caused by the construction of ramparts. The remnants of a former soil or occupational surface have been preserved although they are detectable mainly geochemically. The construction of the ramparts practically makes further natural or anthropogenic erosion of the area of La Terrasse impossible. However, this was not the case before the construction of these ramparts. It is clear that before the onset of the Neolithic or earlier, the surface (and soils) of La Terrasse were repeatedly eroded, probably due to natural processes, exposure of the terrain and the presence of frost-weathered subsoil. With the onset of the Neolithic, erosion was also inhibited/triggered anthropogenically, but its intensity was relatively low because sediments containing artifacts are preserved, although rarely both in the area of La Terrasse itself and under the ramparts that surround it. The mode of preservation, distribution, numbers and recovered species of plant macroremains within the excavated sequences suggest: 1. low intensity of human exploitation in the area; 2. presence of possibly a remnant of a thin ancient cultural layer at the base of section E (70) 90 to 110 cm); 3. anthropogenic and non-local origin of at least some of the charcoal fragments; 4. (strong impact) prevailing vertical bioturbation processes within deposit sequences. The detection of the former surface, i.e., the detection of former archaeological soil at a site with intense erosion is macroscopically almost impossible. The former surface, on which human activities probably took place, was macroscopically very indistinct in the field and its presence was not substantiated by any significant archaeological finds. The best indicator of the former horizon seems to be the CEC as a result of formation of B horizon. This proxy was well developed in the recent part of the soil developed on overburden as well as in the lower part of the layer III. One possibility is that this horizon was a spodic soil horizon. However, based on geochemical analyses, it can be stated that this more or less continuous horizon does not show typical signs of a spodic horizon and, is enriched in elements that document the presence of ash. The burned organic matter was captured to a greater extent in the micromorphological record. At the same time, however, corroded clasts of rock clusters were micromorphologically identified, which, under certain assumptions of retrograde soil degradation, brings back into play the possibility of an original presence of a spodic horizon. At the latest after AD 561, material was deposited on the former surface of the La Terrasse area, which, due to its geochemical composition, suggests the presence of tailings from long term metallurgical activities. Procurement of loosely bound heavy metals points to a weathered state of geological substrate, or more probably, to dissipation of waste arising from the smelting/metal workshop onto the soil. Taking into account that Cu and especially Pb are quite conservative in soil profiles (non-mobile), it could be expected that the metals were introduced to the profiles through a longer lasting activity. The geochemical signal of the newly formed archaeological soil is not typical for long term use because the material of that soil was accumulated quite quickly from the areas with relatively low human impact. The reason for the construction design of the La Terrasse recent morphology may be related to leveling of the surface for other purposes. However, the discussion of the purpose of the construction activities at La Terrasse is not the subject of this paper. In any case, it is clear that the detection of the former surfaces in erosive exposed archaeological sites is always a complex matter and can only be resolved through a combination of field observations, geochemical and micromorphological proxies. The properties of archaeological soils do not necessarily contain a signal of intensive use even when they are located in a suitable morphological area of the site.

5.2. Soils as an environmental record of changes between Iron Age and Medieval occupations at Chotěbuz-Podobora hillfort (Published articles)

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Content

Abstract

The geochemical signal of anthropogenic soils reflects past settlement activities. The soils which are a part of an archaeological archive at a multi-phase hillfort Chotěbuz-Podobora were formed under the significant influence of Early Iron Age and Medieval occupation and various subsequent factors at different parts of the hillfort. The hillfort layout is divided into three parts distinguished by different geomorphological characteristics, the acropolis, 1st bailey and 2nd bailey. While the original morphology of the 1st and 2nd bailey was relatively flat, the acropolis surface was under the slope. All these parts were drilled and detected archaeological strata studied in terms of their geochemical composition and magnetic susceptibility, including its frequency dependence. Finally, the soil horizons typical for each of the part of hillfort were studied micromorphologically. The soil record detected at the site contained high amount of phosphorus, even higher than usually recorded at abandoned medieval villages. Based on areal and stratigraphic distribution were discovered three groups of elements: 1) elements with maxima in "Archaeology" category (Si, P, Ti, Mn, Sr, Zr); 2) elements with maxima in "Topsoil" category (Cu, Zn, As, Pb, LE and Fe, Mn partially); 3) elements with maxima in "C" category (Al, K, Rb and partially Fe). The values of magnetic susceptibility (χ) increased mainly in the topsoil of 2nd bailey. Frequency dependent susceptibility (χFD%) reached the highest values in the archaeological layer with spatial diversity in 1st and 2nd baileys. The high χFD% values confirmed that the Hallstatt horizon at acropolis is redeposited soil, not only redeposited dumping. The oldest human presence is attested by the development of soil reflecting the presence of organic residues. After the first abandonment of the site at the end of Hallstatt period was the organic rich horizon eroded and accumulated at one side of the acropolis. The surface of the acropolis became flatter and levelled. The soil development in the Medieval period was highly influenced by an aggradation of material originally used for different types of building constructions. The presence of anthropogenic elements reflects in that time not only the deposition of organic matter but also the deposition of ash. While the acropolis was heavily occupied, and its geomorphology dramatically changed over time, the 1st bailey served mainly as a production space. The function of the 2nd bailey stays unsolved due to its poor preservation. The most recent human influence in the soil record is visible in the topsoil; first as the result of agricultural practices and second as the contamination by Pb and magnetic particles resulting from the atmospheric pollution.

Keywords: Geoarchaeology, Geochemistry, Magnetic susceptibility, Micromorphology, Pedology.

Introduction

Sediments and artifacts are the essential material archive used by archaeologists to reconstruct the past climatic conditions and influence of human activities for the reconstruction history of the site. Human influenced soils may develop as a result of long term or intensive use of the site. Their soil terminology is not always clear. The nature of such soils is usually variable depending on the geological substrate, population density, building materials, climate and activities that took place on the site. For these explanations, it is possible to categorize them as a specific sub-category of anthropogenic soils such as Anthrosols and Technosols (Holliday, 2004; Soil Survey Staff, 2014; Howard, 2017). Human settlement activities tend to the accumulation of various elements as for example P, Ca, K, Mn, Fe, and Cu (Hillman et al., 2015; Homsher et al., 2016; Šmejda et al., 2017; Devos, 2018; Van Gils and Mölder, 2019; Wouters et al., 2019; Fernandez et al., 2002). The long-term intensive human settlement activities such as domestic/organic waste disposal, craft production, prescribed burning of the forest, farming, animal husbandry, and agriculture can result in the formation of archaeological anthrosols (FAO, 2008; Motsara and Roy, 2008; Devos et al., 2011; Soil Survey Staff, 2014; Howard, 2017; Devos et al., 2021). The minor nutrients, also directed to as micronutrients or trace elements, supplied by the soil are molybdenum, copper, zinc, manganese, iron, nickel, boron, selenium, and chlorine (Bunt, 1988). In the natural soil procedure, healthy ecosystems soil nutrient levels are maintained by the nutrient cycle and are relatively stable (USDA and Soil Survey Staff, 2010; Soil Survey Staff, 2014). Recent or sub-recent anthropogenic fertilization such as application of weedicides, lime, fertilizers, and atmospheric deposition can alter the soil by the loading of some elements (Janovský et al., 2020a,b). Such patterns develop when past human activity modifies the physicochemical and biological soil properties, which affect the distribution of natural and anthropogenic elements loadings (Terry et al., 2004; Šmejda et al., 2017; Horák et al., 2018; Janovský et al., 2020a).

The case study Chotěbuz-Podobora hillfort offered a well-preserved record of human influenced soils dated to the time span between the Hallstatt to Medieval period and aimed us to determine whether minor/ microelements in combination with magnetic proxies and micromorphological control are suitable proxy indicators of past human activities. Based on our research we tried to answer the questions: (a) to what extent the distribution of waste could affect the geochemical composition of soils? (b) how recent and sub-recent conditions may influence the soil records? (c) how geological substrate could affect the geochemical composition of soil? (d) which method is appropriate to apply for this type of study?

Regional settings and history of research

Geology, morphology and climatic factors.

Hillfort in Chotěbuz-Podobora is situated on a low watch tower about 5 km north of Český Těšín. Its total area is 1.74 ha and consists of three fortified parts – acropolis, 1st, and 2nd bailey. While the surface of the 1st and 2nd bailey is naturally flat, the surface of the acropolis was originally (i.e., during the prehistoric times) under the slope. This fact resulted into the accumulation of the thick cultural layer, reaching more than 1.5 m on the north-western part of the acropolis (Figure. 1). From the point of geology is the hillfort located at the forehead of the Carpathian mantle on a ridge that falls steeply into the floodplain of the Olza River to the east and northeast. The geological substrate of the hillfort is built of rocks of the Silesian unit of the Carpathian mantle typical by alternating sandstones and clay-stones. In the peripheral parts, especially on the slopes near the river floodplain, there are rare small outcrops of picrite's and těšínites or their tuffs. In the top part and on the slopes, the rocks of the Carpathian flysch are covered with a continuous layer of loess-like deposits or eluvium. Loess-like deposits are usually partially or completely decalcified. In the area of the hillfort and it's surrounding the soil types are represented by haplic Luvisols to a lesser extent as of cambisols. According to Quitt (1971), the climatic conditions correspond to the slightly warm area of MT 10 (Köppen classification Cfb; Tolasz et al., 2007), where the average annual temperature is slightly above 7 degrees Celsius, and the average annual precipitation is in the range of 700–750 mm. The western and north western wind currents significantly predominate in the area (Figure. 1).

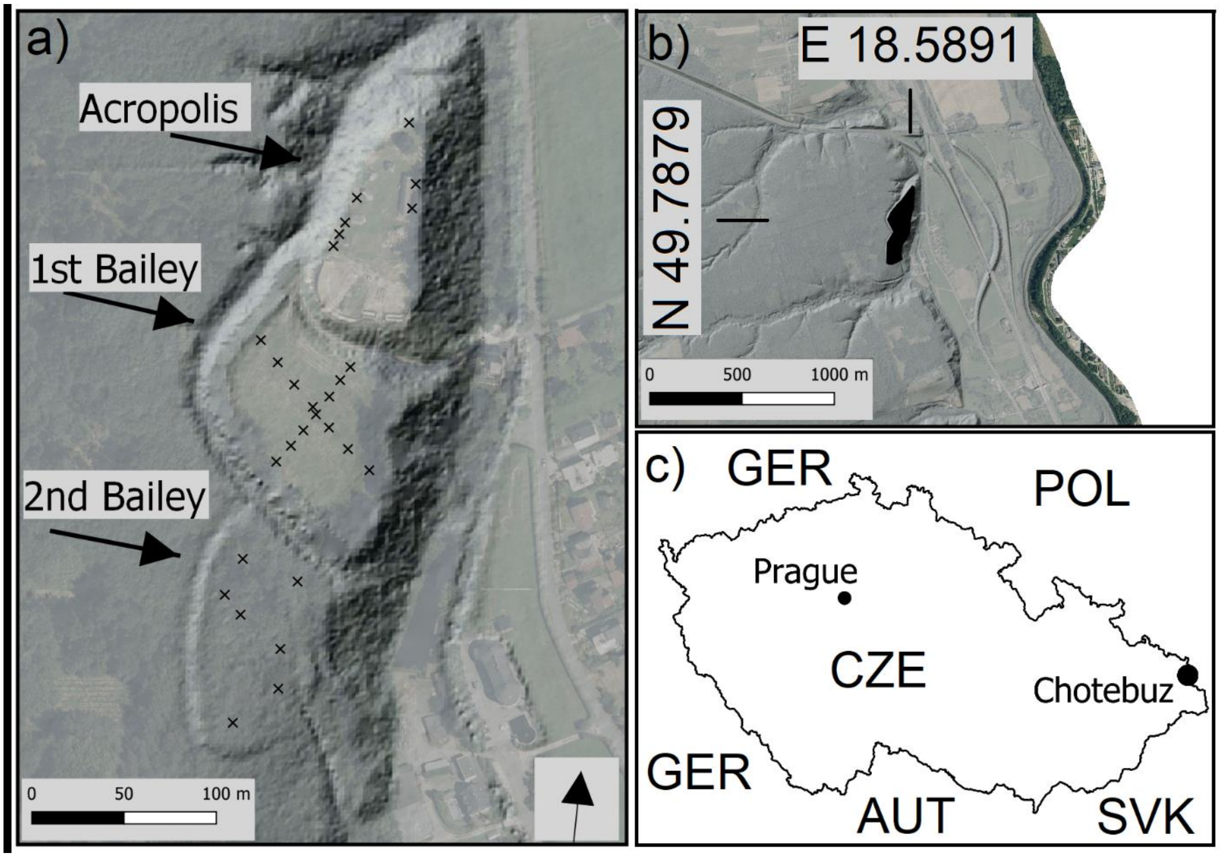

Figure. 1. The hillfort Chotěbuz-Podobora and its surroundings: a) depicts the plan of the hillfort showing the position of the acropolis and the 1st and 2nd baileys, as well as the position of the core sites depicted by symbol ×; b) also depicts the position of the hillfort in the regional context (hillfort as a black polygon), as it was placed on the margin of upland above broad valley of Olše / Olsza River (which is located on the Czech / Polish border); c) is position of Chotěbuz-Podobora in context of Czechia (Chotěbuz-Podobora as a black circle) in the context of Czechia and neighbor countries Germany, Poland, Austria and Slovakia. Local and regional map are depicted with background by aerial photo with terrain digital model (sourced by the Czech Cadastral Institute).

Archaeology of the site

Site history

Hillfort in Chotěbuz-Podobora was in past occupied in two main phases with one thousand years of hiatus between them. The first phase is represented by Hallstatt period and the second one by Slavic period. The long-term anthropogenic impact on this area formed not only soil record but also influenced significantly the recent morphology. The site consists of three fortified parts, of which the highest is the acropolis adjacent to the south by two fortifications. The area south and west of the fortified settlement was used in various intensities as settlement, but probably not fortified. From the eastern side, the watchtower sloped sharply to the Olša River, and from the north it was additionally protected by a smaller rampart. The first excavations of the site dates to the beginning of the 20th Century, followed by Victor Karger (1913,1914) and Lumír Jisl (1952, 1954). The hillfort was systematically excavated by Pavel Kouřil during the seasons 1978 –2014 and 2017– 2019 (Kouřil, 1994; Kouřil, 1997; Kouřil, 2007; Kouřil and Gryc, 2011; Kouřil and Gryc, 2018; Kouřil and Gryc, 2019). The most researched part is the acropolis and the area of the first bailey adjacent to the inner rampart.

Occupation of the Hallstatt period

The prehistoric settlement of the locality is associated with the Lusatian culture, and its heyday falls in the Early Iron Age. The relative chronology created by P. Reineck and his successors for the territory of southern Germany divided the period of the Bronze Age and the Iron Age into several stages. Although Reinecke's system is not fully applicable for the area under discussion, it is considered the common denominator of local periodization systems (Przybyła, 2017; 193-195). According to this breakdown, we place the beginning of settlement of the hillfort at the end of the Bronze Age (Ha B2-3), the greatest flourishing is observed in the earlier Iron Age (Ha D), and it was inhabited to a limited extent even at the beginning of the Late Period (Lt A) (Table. 1).
Absolute dating of periodization for Czechia based on Jiráň (2008); Venclová (2008); Jiráň and Venclová (2007–2008); Sady (2012); Przybyła (2017). Phases of Bronze and Iron Ages in Southern Germany (Przybyła, 2017, s. 195).

Phases of Bronze and Iron Ages in Southern Germany (Przybyła, 2017, s. 195)		Phases of Bronze and Iron Ages in Czechia (Venclová, 2008; s. 26; Jiráň, 2008, s. 144-145)		Dendrochronology, radiocarbon dating (Venclová, 2008, s. 26)
400	Lt A		Lt A 450	Lt A 460

<table>
<tr><td rowspan="6">600</td><td>Ha D3</td><td rowspan="2">500</td><td rowspan="3">Ha D2-3
550</td><td></td></tr>
<tr><td rowspan="5">Ha D2</td><td>480
Ha D3
500</td></tr>
<tr><td rowspan="4">600</td><td rowspan="2">Ha D2
530</td></tr>
<tr><td rowspan="3">Ha D1</td></tr>
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Ha C2
Ha C1</td><td rowspan="6">700</td><td rowspan="2">Ha C3
650</td><td></td></tr>
<tr><td>625
Ha C2
650</td></tr>
<tr><td rowspan="2">Ha C2
725</td><td>660
Ha C1b
720</td></tr>
<tr><td rowspan="2"></td></tr>
<tr><td rowspan="3">Ha C1</td></tr>
<tr><td rowspan="2">730
Ha C1a</td></tr>
<tr><td>800</td></tr>
</table>

	Ha B3		(Ha B2) Ha B3	
	Ha B2	925		
1000	Ha B1	1025	Ha B1	

First phase of hillfort occupation is concerned mainly in the northern part of the acropolis. The remains of a light fence were discovered under the body of the wall separating the acropolis from the 1st bailey. It can be dated to the end of the Ha C1a or at the beginning of the Ha C1b. The acropolis was additionally divided into two parts. The moat, which intersects the acropolis in about two thirds, and the accompanying light palisade. From the west, east and north sides, the acropolis was perhaps only lightly fortified with a simple palisade. The fortifications were sometimes destroyed and rebuilt during the Hallstatt period, while the rampart was significantly widened, raised and fitted with a wooden palisade. The demise of the fortification's dates to the course of stage RHD2-3 (Tůma, 2008; 2010). In several places, housing estates of the Hallstatt period and perhaps even the early La Tène period were destroyed into the destruction of the Hallstatt fortifications. The intensive settling of the fort ends during the Ha D3 stage, but some of the findings would suggest that the settlement may have survived here during the Lt A (Table. 1).

In general, we can state that the acropolis was permanently inhabited, and the area was intensively used until the end of the prehistoric phase. This is evidenced not only by the thickness of the cultural layer, but also by its very intense saturation with macro-remains of plants and animal bones. It can be assumed that the development consisted of smaller homesteads without a visible arrangement, which included objects of various functions. The accumulation of objects indicative of handicraft production (metal workshop, weaving, free-standing heating installations) would also indicate that the acropolis area was rather reserved for the elite and specialized craftsmen; cattle housing, activities related to agriculture and farming were then located outside the acropolis.

The area of the 1st bailey was occupied mainly in the stage RHC1b - RHD2-3 (Table. 1). There was recorded a torso-shaped preserved rampart with an inner moat on the eastern side of the watchtower dated to the prehistoric times. Most of the recorded buildings were concentrated in the immediate vicinity of the hypothetical fortifications, while the central area seems to have remained undeveloped. These were mainly recessed pits of amorphous shape, containing innumerable and very fragmented ceramic material, which often accompanied pile pits and distinctive hearths. Fragments of iron slag or landfills of burnt tees - raw materials most often used as an admixture of ceramic dough were also found in some of the buildings. Due to the absence of buildings in the central part, the refugial function of this part of the bailey or its use for economic activities was considered.

Significant traces of settlement were also documented in the area of the 2nd bailey. In all probes, both the cultural layer and objects that can be associated with the Hallstatt period were recorded. The objects contained innumerable ceramic fragments (among other things decorated with solidified fragments of cups of the oldest phase), and fragments of slag, heavily secondary burnt-out fragments of ceramics (probably secondarily used for production purposes) or landfills of burnt solids (Table. 2).

Occupation during the Slavic period

After almost a thousand years of hiatus, the area of the fortified settlement was repopulated by new settlers. The oldest phase of new occupation which concentrates again to the northern part of acropolis, and which can be captured mainly in the form of ceramic fragments, dates to the second half of the 8th century. It is probable that the first Slavs used mainly the remains of the older fortifications and the new fortifications were built during the 9th century AD. The rampart was raised, the ditch was deep ended, and the crown of the rampart was fitted with a wood-clay chamber structure. The construction was preceded by extensive landscaping and the entire western side was levelled, using mainly gravelly soil coming from a deepened ditch. As in prehistoric times, the northern part of the acropolis was delimited in the 9th century by a moat and additionally protected by a more massive wooden structure. The archaeological structures dated to this period consist of above-ground or partially sunken buildings containing otherwise standard ceramics and finds. Housing animal shelter with the production building (blacksmithing) was identified in the southern part of the 1st bailey. As in prehistoric times, the buildings were concentrated almost exclusively along the inner base of the fortifications, and it seems that some of the buildings were directly connected to the inner wall of the wall. Due to the nature of archaeological finds, this part of the fort appears to be a district intensively used for economic activities, especially the processing of grain is obvious (Kuna and Křivánková, 2006; Kouřil and Gryc, 2018).

Table. 2. Number of samples in soil / stratigraphy and area categories.

Simple Categories	Fine Categories	A (Acropolis)	1 (First Bailey)	2 (Second Bailey)	Summa
T (Top soil)	T (Topsoil)	0	42	23	65
	L (Leveling)	11	0	0	11
AR (Archeology)	EM (Early Medieval)	16	7	0	23
	EM9	17	0	0	17
	CH (Charcoal Layer)	0	4	0	4
	H (Hallstatt Layers)	84	15	0	99
	B (Soil B horizon)	0	28	30	58
C (Soil C horizon)	C (Soil C horizon)	6	41	10	57
Summa		134	137	63	

The occupation intensity of the 2nd bailey seems less significant for Slavic period, but whole part has been used since the beginning of Slavic settlement, as evidenced by both the finds of pottery and objects of an exceptional nature (spur with hooks). During the 9th century, the construction of the fortification began, but was never completed. Research with a metal detector then revealed numerous findings of slag, which, however, could be related to both the older (9th century) and younger (2nd half of the 10th century - 1st half of the 11th century) phases of Slavic settlement.

Abandonment of the site

At the turn of 9 to 10th century, the entire fort was forcibly destroyed. In the area of the acropolis, mainly buried structures were identified. Finds of grinding stones confirm grain processing, frequent finds of iron processing slag and lead ingots prove lead processing directly on the acropolis. During the second half of the 11th century, the castle was forcibly destroyed and definitively abandoned.

Figure. 2. Sections showing where samples were collected (i) acropolis., (ii) 1st bailey, (iii) 2nd bailey.

Methodology

Sampling strategy

The main aim of the sampling was to cover all three parts of the hillfort to get an idea of how the geochemical composition of the soil record differs in time and space. All sampling was done from coring (Figure. 1). The situation at the acropolis is quite complex and the sedimentary record differs according to the position (higher thickness in the NW part). The archaeological excavations which were done there just a few years ago gave possibility to control the sedimentary record from cores with the archaeological documentation done. The natural morphology of the 1st bailey is flat, and the thickness is constant there. Therefore, we used cross sampling of whole area. The second bailey is heavily turbated and the archaeological situation there is not very clear. The sampling strategy was to cover the general information from the site and therefore the cores were positioned in places where the historical sediments and layers are intact and well known and documented from previous archaeological research (Figure. 2).

Pedological description and characterization of horizons for statistic

The pedological description of the cores brings important information about the nature of the soil record. During the description the main aim is concerned to the color, and some other pedological properties. The color of sediments was identified in both wet and dry states using a Munsell soil color chart. Soil color and other factors containing texture, structure, and consistency have been used to determine and specify soil layers and to group soils according to the soil classification system (USDA and Soil Survey Staff, 2010; Liles et al., 2013; Sawada et al., 2013; Soil Survey Staff, 2014).

Soil color has been used as one of the key characteristics to determine horizons in a profile and to categorize soil types in a territory. Regular measurement of soil color has often been accomplished in the field by visually comparing a soil sample with the chips of standard color charts (Munsell, 1905).

For describing and lately interpreting and visualizing the categories, we used the categorization of hillfort areas into horizontal layers called horizons ("T" for topsoil described at acropolis, 1st and 2nd bailey, "L" for recent levelling at acropolis, "EM" for early medieval horizons, "EM9" for 9th century early medieval horizons, "CH" for dark horizon located at 1st bailey (see Figure. 3), "H" for Hallstatt, "B" for soil B horizon at 1st and 2nd bailey and "C for soil C horizon"). The simple categorization had categories "T" (combining topsoil), "AR" for archaeology (combining all archaeological layers and soil B horizon), and "C" for soil C horizon.

Soil micromorphology

Soil micromorphology is the study of soil substrate via oriented thin sections. While the analytical method will show the general composition of the soils, the soil micromorphology may reveal much more information related to the primary and post sedimentary formation processes. There was sampled in total 16 small thin section of the diameter 2.5 – 3.5 cm. Material for thin section was taken from the cores at acropolis, 1st as well 2nd bailey from the horizons where any lithological change was visible. The dating of the timespan of accumulation is based on archaeological knowledge of this site. The samples were packed into clink foil and transported to the laboratory, dried and impregnated in vacuum by resin Polylite 2000. After curing thin section of the thickness of 30 µm were done from them. Those sections were studied under the polarizing microscope at the magnifications ranging 16 – 400× and described according to Stoops (2003), Stoops et al. (2010) in Supplementary material 1, 2 and 3.

Analytical method

Portable X-Ray fluorescence (pXRF) is a non-destructive analytical technique that provides near-instantaneous elemental analysis of materials. This technique is unique to the elemental composition of the sample. Because each element has its characteristic, and pXRF can tell exactly what elements are in the sample and in what quantity, can be operated in the field anytime (anywhere), and provide fast acquisition of geochemical data for rapid delineation of anomalous zones and the in-depth, quantitative analysis of metal content for geochemical mapping. (Potts et al., 1997; Kalnicky and Singhvi, 2001; Markowicz and Van Grieken, 2002; Sitko, 2009).

We processed the analytical stage this way: we dried the samples at 40 °C for 24 hours. Then, the material was sieved on 2 mm mesh sieve and resulting fraction was grounded in porcelain mortar. We used a portable ED-XRF (pXRF) analyser (the device model was “Delta Professional” by Olympus InnovX). The mode “Soil Geochem” was used and every sample was measured for 30 s by 10 kV beam (better measurement of lighter elements) and for 30 s by 40 kV beam (better measurement of heavier elements). Results are in weight ppm. The quality of the device measurements was successfully tested on 55 reference materials. This process was used in several of previous studies (e.g., Horák et al., 2018; Janovský et al., 2020a,b; Danielisová et al., 2022). Such processes are in good reliability with more developed and established laboratory techniques (Save et al., 2020).

Magnetic susceptibility proxies

The magnetic properties of the soil minerals depend essentially on the Fe content, because Fe is 40 times more abundant than the sum of all other magnetic elements in the earth’s crust (Coey, 1987), and Fe-oxides such as magnetite and maghemite are ferrimagnetic (Cornell and Schwertmann, 2003) and can be easily identified due to their very intense response to external magnetic field. Magnetic susceptibility measurements were performed in the Laboratory of Rock-Magnetism in the Institute of Geophysics, Czech Academy of Sciences. Bulk samples were used to measure volume-specific magnetic susceptibility (κ, SI) by using an MFK1-FA Kappabridge device (AGICO, Brno, Czech Republic) (Pokorný et al., 2011). Each sample was measured twice at two operating frequencies, f_1 = 976 Hz and f_3 = 15 616 Hz. Readings of the unconsolidated samples were taken in plastic bags; the measured susceptibility values were normalized by the mass of each sample and expressed as mass-specific magnetic susceptibility [χ, m^3/kg]. Magnetic susceptibility refers to the concentration, size and character of Fe-oxides minerals, and can be detected even in trace quantities in any rock, soil, or even in organic tissue (e.g., Thompson and Oldfield., 1986). Frequency-dependent magnetic susceptibility, $\chi_{FD}\%$, is a particular property of ultrafine, superparamagnetic grains, which result from pedogenic processes (e.g., Maher, 1986). This parameter was characterized by the following commonly accepted formula:

$$\chi_{FD}\% = 100 \times (\chi_{LF} - \chi_{HF}) / \chi_{LF} \qquad [\%],$$

where χ_{LF} and χ_{HF} are mass-specific magnetic susceptibilities determined for frequencies f_1 and f_3. (Dearing et al., 1996; Hrouda, 2011).

Magnetic susceptibility refers to bulk sample properties in contrast to (electron) microscopical techniques where only a small fraction of a sample can be analyzed. From the analytical perspective, magnetic susceptibility is frequently used due to its sensitivity, rapidity, ease of sample preparation, comparatively modestly priced instrumentation for data acquisition, non-destructiveness, and in particular the ability to sense grain-size variation in the ultrafine grain-size range. Therefore, magnetic susceptibility parameters are well suited as proxy parameters (e.g., Fialová et al., 2006).

Dataset characteristics

The statistical software R in version 3.6.0. was applied for the data analyses. The final dataset (Supplementary material 4) consisted of 334 samples and these elements: Al, Si, K, P, Ti, Mn, Fe, Cu, Zn, As, Rb, Sr, Zr, Pb and LE. Abbreviation LE stands for “light elements” and is aggregate expression of the content of elements from H to Na, which can be detected by pXRF, but cannot be distinguished. Although it is not an elemental content, but rather quasi-elemental variable, we usually use it in analyses anyway, as it bears proxy information (and usually tends to be connected to the topsoil or organic material (Horák et al., 2018). The basic statistical characteristics are presented in Table. 5. There were also some unmeasured values in used dataset (3 samples in case of P). We computed these missing values by using function impKNNa (R package rob Compositions (Boogaart et al., 2010), which is suited for such tasks when working with geochemical data. There were used mainly exploratory visualization techniques like boxplots and scatterplots. For testing the diversity between categories, we used Kruskal-Wallis test. We also used multivariate analysis (principal component analysis: PCA). We performed it in two ways: on elemental content data, and on such data after ilr-transformation (ilr-transformation is part of log-ratio transformations which are suitable for compositional data like geochemical data - Reimann et al., 2008). Both approaches emphasize different aspects of the dataset, and their combination can uncover interesting patterns.

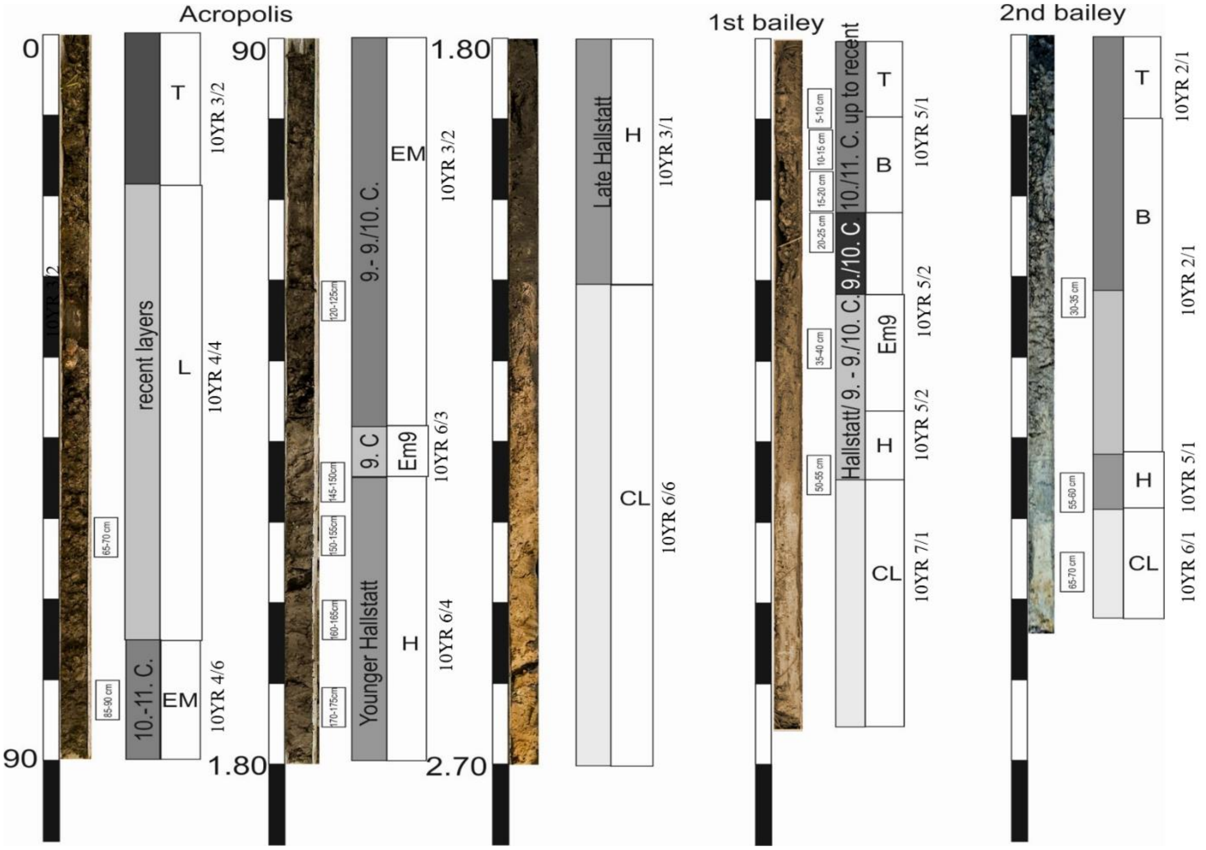

Figure. 3. General view on sedimentological record preserved in three parts of hillfort (Acropolis, 1st bailey and 2nd bailey), together with stratigraphic units, the micromorphology sampling position and codes for geochemical sampling. The stratigraphic units are described in detail in the chapter 3.2.

Results and interpretations

Pedology and micromorphology

Acropolis

The sedimentary record of the acropolis varies significantly, because the accumulation of the soil material is influenced by the natural sloping of the site. The thickness of the soil in NW part is much thicker than the soil on E part of acropolis (Figure. 3). The soil record in NW part is thicker than on E part of acropolis. Macroscopically was possible to divide minimally 4 layers differing by color from 10YR 3/2, 4/4, 4/6, 3/2, 6/3, 6/4, 3/1, and 6/6 with the texture of clay, clayey silt, and silty clay. The transition between single horizons is always abrupt. Archaeologically is possible to link those layers to the different occupational periods, i. e. horizon accumulated during Hallstatt period, horizon accumulated during 9th century, horizon accumulated during 9th to 10th century, horizon accumulated during 11th century and recently accumulated horizons (Figure. 3). Key morphological characteristics of studied soil horizons at acropolis were, easily demarcated, ranging from clear to abrupt with either wavy or smooth horizon topography. Well drained parts with very dark grayish brown clay (10YR 3/2) topsoil “T” overlying leveling part “E horizon” with dark yellowish brown (10YR 4/4) with clayey silt (Figure. 3) texture. Abundant distinct clay at L horizons was observed in the indicating eluviation-illuviation as dominant pedogenic process. EM layers had colors (wet- Field condition) between dark yellowish brown (10YR 4/6- deep) to dark brown (10YR 3/2- top); EM9 with pale brown (10YR 6/3), Hallstatt from light yellowish brown (10YR 6/4- deep) to very dark gray (10YR 3/1- top) (Figure. 3). With clay texture, and CL with brownish yellow (10YR 6/6).

Micromorphological samples taken from the core at acropolis revealed fundamental differences between the archaeological layers related to the different timespan of acropolis occupation (see Supplementary material 1). The layers accumulated during the Hallstatt period show significant laminar microstructure (Figure. 4A). They consist of single thin laminae of redeposited material rich of phosphates (bones, burned bones, phosphatic pedofeatures), organic matter in different state of decomposition, charcoal, microcharcoal, fragmented clay coating and mineral fraction (Figure. 4B). Another typical pedofeature relates to the origin of Fe/Mn nodules and present depletion, reflecting changing oxidation/reduction environment. Contrary to it there is visible change in microstructure in the layer accumulated in 9th century and later. The layer typical for 9th century doesn’t show any sign of lamination (Figure. 4C), but its composition stays the same. The layers representing period of accumulation during 9th– 10th century has a lack of phosphatic features and Fe/Mn features are quite rare there. The material of this layer is also less-sorted (Figure. 4D). The layer typical for 10th– 11th century shows again the signs of oxidation/reduction processes reflected in common presence of Fe/Mn nodules and strong depletion (Figure. 4E). The matrix is in this period well sorted and the significant is high bioturbation. The recent layers consist obviously of the destruction of different material, the matrix is unsorted, with several different types of pores, depletion and accumulation features and the presence of rock fragments as well as soil aggregates floating in the space (Figure. 4F).

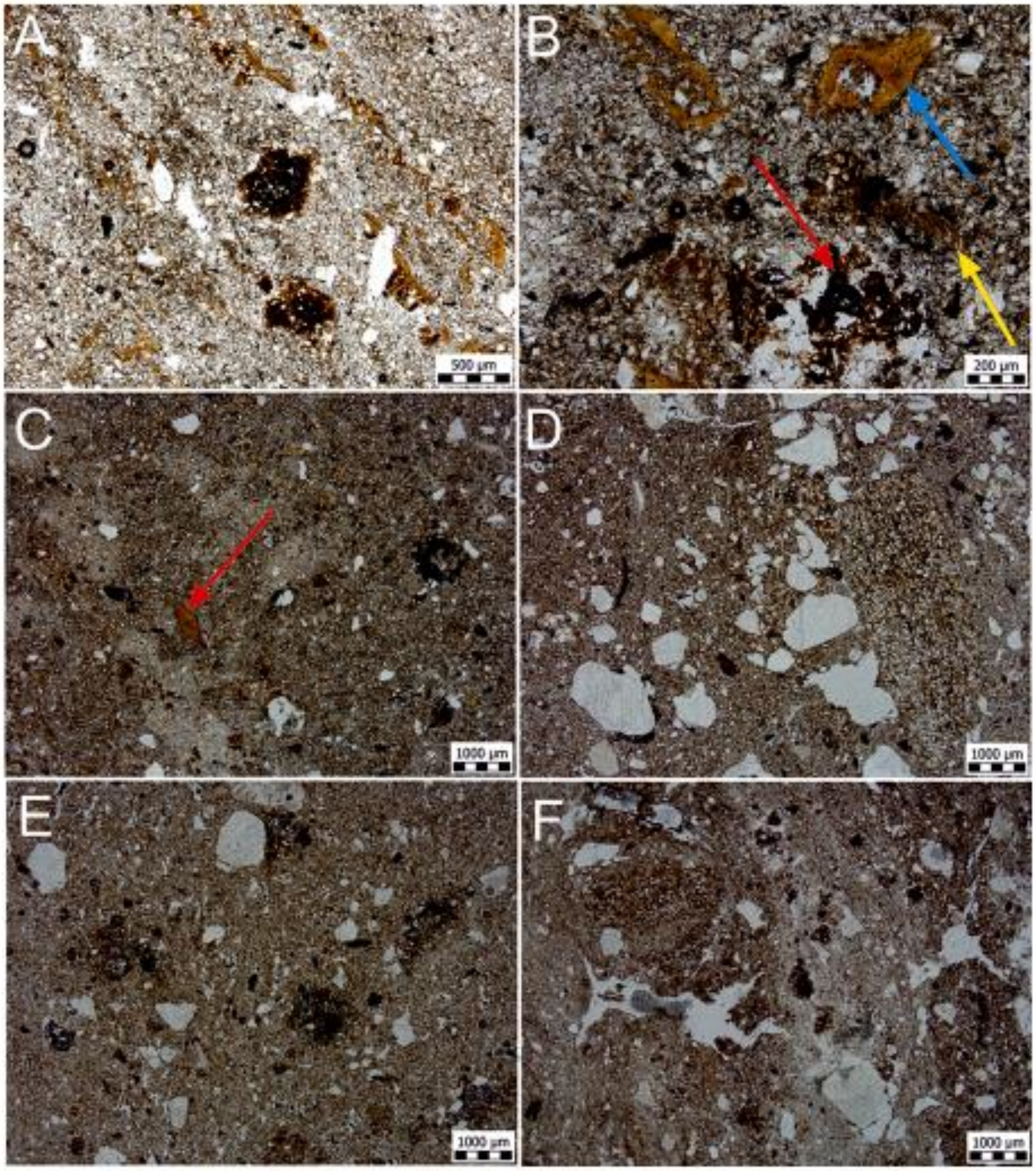

Figure. 4. Micromorphological documentation of the main differences between soils accumulated in different timespan at acropolis; A – Hallstatt period (Table. 1) is typical by the appearance of laminated substrate (detected in three different thin sections). Note the presence of oriented, but fragmented clay coating, widely distributed microcharcoal and the in situ origin of Fe/Mn nodules (in the center); B – Another typical features for the layers accumulated during Hallstatt period are phosphatic accumulations (neoformations, see the blue arrow), presence of decomposed organic matter (red arrow) and clay coating often connected with the presence of charcoal (yellow arrow);

C – layer accumulated in 9th century has often similar composition as Hallstatt layer but it is not laminated and it is often heavily bioturbated; D – 9th – 10th century layers are less sorted and there is noticeable lack of phosphatic features, clay coating and bones; E – 10th to 11th century layers are moderately sorted, they have lack of phosphatic features and clay coatings, but Fe/Mn nodules are very common; F – recent layers are mechanically heavily turbated, unsorted with the presence of fragmented clay coating microcharcoal and in situ Fe/Mn nodules (all photos are taken in plane polarized light – PPL).

1st bailey

The soil record of the first bailey is typical by stable thickness and the appearance of horizons with colors from 10YR 5/1, 5/2, to 7/1 (Figure. 3) with clay, silty clay, clayey silt texture. The transitions between single horizons are always abrupt. According to archaeological findings was possible to link single horizons to the single timespans of occupation, often with the overlapping. The micromorphological description revealed further details. The first micromorphological sample taken from the depth of 50 – 55 cm should represent the beginning of Hallstatt occupation at the site. The matrix is typical by intensive depletion and the presence of Fe/Mn nodules (Figure. 5A). These Pedofeatures are linked to the changing oxidation/reduction environment. The layer is also typical by the presence of charcoal and microcharcoal (Figure. 5A). The timespan interpretation of the sample from the depth 35 – 40 cm is more complicated and was suggested as the transition between Hallstatt, 9th and 9 – 10th century. Morphological characteristics of studied soil horizons at first bailey were partially easily demarcated. Less drained parts with gray (10YR 5/1) for “T”, and “B” horizons, grayish brown (10YR 5/ 2) for “EM9” and Hallstatt and light gray (10YR 7/1) for “CL” with clay, silty clay, clayey silt soil textures (Figure. 3). It differs from the sample below fundamentally. Its composition is variable due to the presence of different rock fragments and daub (Figure. 5B). It also contains a high number of charcoal and Fe/Mn nodules, but the depletion is presented only locally. Interesting results were revealed from the darker horizon at the depth of 20 – 25 cm which is archaeologically aid to the timespan of 9th– 10th century. This layer is typical by the presence of Fe impregnations and limonite neoformation (Figure. 5C). The number of charred materials is not higher than in other samples and it also contains fragmented clay coating. It is quite probable that this layer relates to the metalworking practices at first bailey. The remaining three thin sections represent the wide timespan from 10 to 11th century up to recent times. This horizon is extremely variable in composition, it contains different rock fragments and daub (Figure. 5D). The presence of Fe/Mn nodules together with the depletion reflect variable oxidation/reduction environment. The presence of charred material is documented but the presence of bone fragments or clay accumulation is lacking (see Suplementary material 2).

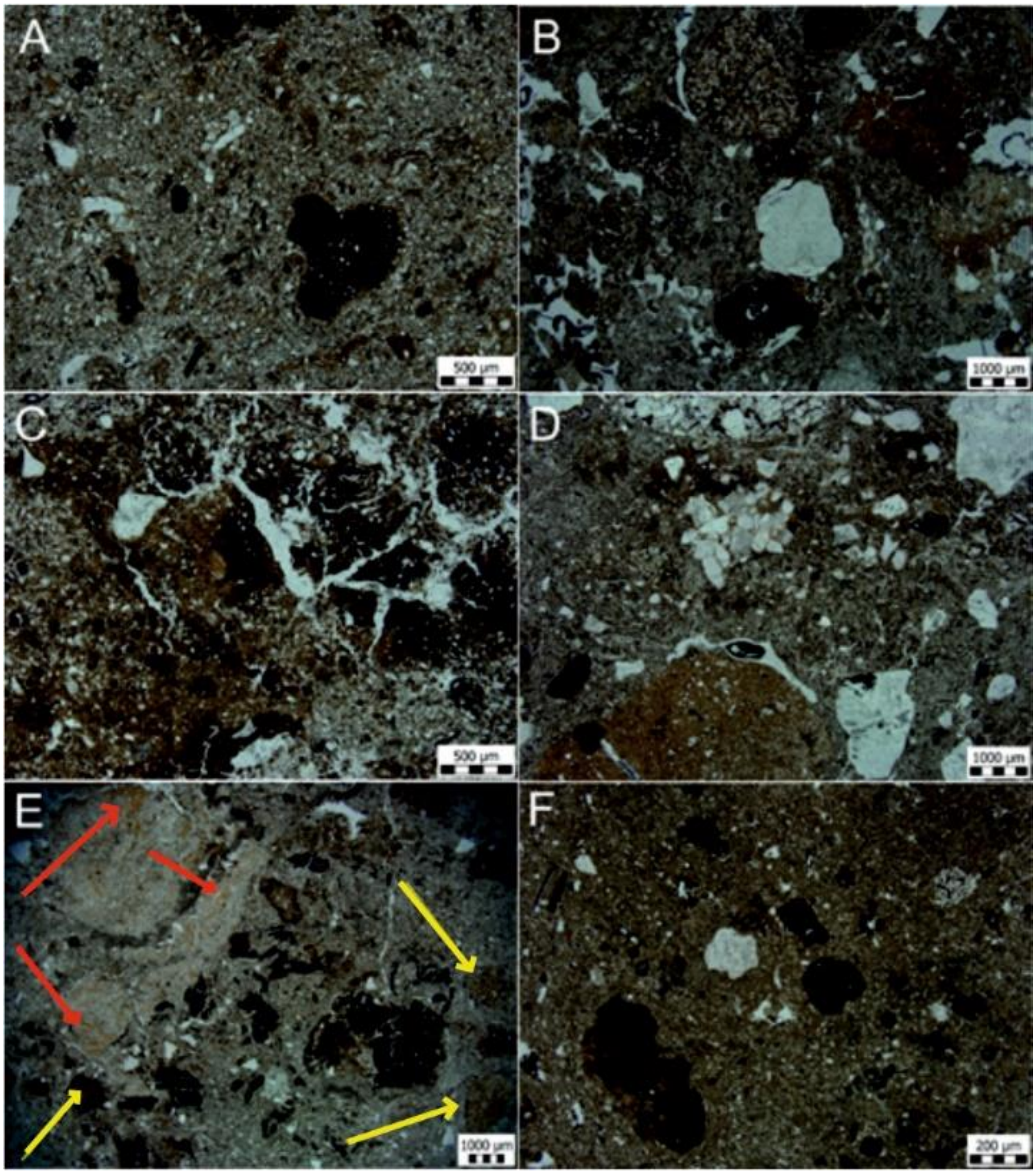

Figure. 5. Micromorphological documentation of the main differences between soils accumulated in different timespan at 1st and 2nd bailey; A – Hallstatt horizon of the 1st bailey, depleted and rich of Fe/Mn nodules; B – unsorted horizon of the timespan from Hallstatt to 9th and 9th to 10th century at 1st bailey; C – dark horizon dated as 9th to 10th century at 1st bailey with a noticeable appearance of limonite neoformation and Fe/Mn concentrations; D – unsorted uppermost soil horizon at 1st bailey dated to the spam 10th-11th up to recent. There is a high appearance of daub and rock fragments in locally depleted matrix with common passage features; E – probably Hallstatt horizon at 2nd bailey typical again by the depleted matrix, fragments of the local geological substrate (red arrows), charred organic matter and Fe/Mn nodules (yellow arrows); F - relatively homogenized horizon of soil from the depth of 30 – 35 cm at 2nd bailey. The timespan of accumulation is not known, but matrix is not depleted and contain several charred organic matter and Fe/Mn nodules.

2nd bailey

The soil record of the 2nd bailey showed to be relatively well stratified, but archaeological interpretation was not possible to suggest due to the low knowledge about the archaeological findings in this area. Micromorphology partly suggested possible dating according to similarities with the horizons excavated at acropolis and at 1st bailey (see Supplementary material 3). Macroscopically was possible to divide minimally 3 layers differing by color from 10YR 2/1, 5/1, and 6/1 with texture of clay, clayey silt and silty clay. The thin section taken at the depth of 65 – 70 cm reflects the composition of non-human influenced geological substrate. It is generally composed of depleted clay loam with the abundance of clay accumulations and the Fe/Mn nodules development. The composition of the aggregate of the substrate is nicely visible at Figure. 5E (red arrows). The sample taken in the depth of 55 – 66 already document clear human impact. The composition of this horizon is very similar to the Hallstatt horizon at 1st bailey, and partly to the Hallstatt horizons at acropolis. Generally, represents depleted silty loam with a high abundance of charred material (Figure. 5E) and several Fe/Mn nodules documenting changes in oxidation/reduction environment. The sample from the depth of 30 – 35 cm documents some later phase of occupation. There is not visible any depletion, but the presence of Fe/ Mn nodules is noticeable (Figure. 5F). Morphological characteristics of studied soil horizons at second bailey was not easily demarcated. Less drained parts with black (10YR 2/1) at topsoil and B horizons, gray (10YR 5/1) at Hallstatt and “CL” (10YR 6/1) horizons (Figure. 3).

Analysis of pXRF

Element content

The elementary composition of studied soils is quite similar to those studied by Salisbury (2020) at central European sites. Usually, the phosphorus (P) in soils reach thousands of ppm. The soils at Chotěbuz Podobora site had the mean and median of P 3648 ppm and 3015 ppm respectively. The basic statistical characteristics of the elements in analyzed dataset is at Supplementary material 5. The content of P was also higher than in usual not so intensively influenced environment of deserted medieval villages, where P content usually reached only hundreds of ppm (Horák and Klír, 2017; Horák et al., 2018; Janovský et al., 2020a,b). Kruskal-Wallis tests showed that there was prevailing diversity of the elemental content between the categories of area (“A”, “1”, “2”) and stratigraphy (“TL, “AR”, “C”) and between their combinations. All elements were tested different except of Al and Fe (between areas), Si (between stratigraphy). According to the elemental distribution we could distinguish three groups of elements (Figure. 6 and Supplementary material 6, 7 and 8 in details) representing interpolated maps of elemental content and boxplots (Figure. 7 and supplementary material 9, 10 and 11 in details): 1) elements with maxima in “Archaeology” category (Si, P, Ti, Mn, Sr, Zr); 2) elements with maxima in “Topsoil” category (Cu, Zn, As, Pb, LE and also Fe partially and Mn partially); 3) elements with maxima in “C” category (Al, K, Rb and partially Fe). Here we comment only on interesting and outstanding results and indications. Only some elements from first group (P, Mn, Sr) recorded distinguished diversity between the categories, and the maxima were reached mainly in archaeological layers of acropolis and 1st bailey (categories “A” and “1”) and in stratigraphic layers dated to Early Medieval 9th century and Hallstatt (categories “EM9” and “H”). The other elements from this group (Si, Ti, Zr) did not record such distinguished variability. Elements from second group (Cu, Zn, As and Pb) reached high values in topsoil of 1st and 2nd baileys (categories “T”, “1”, “2”), but Cu and Zn reached similar values also in archaeological layers of acropolis, where As and Pb reached low values (categories “A”, “EM”, “EM9”, “H”). Some elements from third group recorded interesting patterns: Aluminum (Al) distinguished very well C horizon from any other material by values higher than 60,000 ppm, Rubidium (Rb) recorded interesting bimodal distribution in Hallstatt layer in acropolis (categories “A”, “H”).

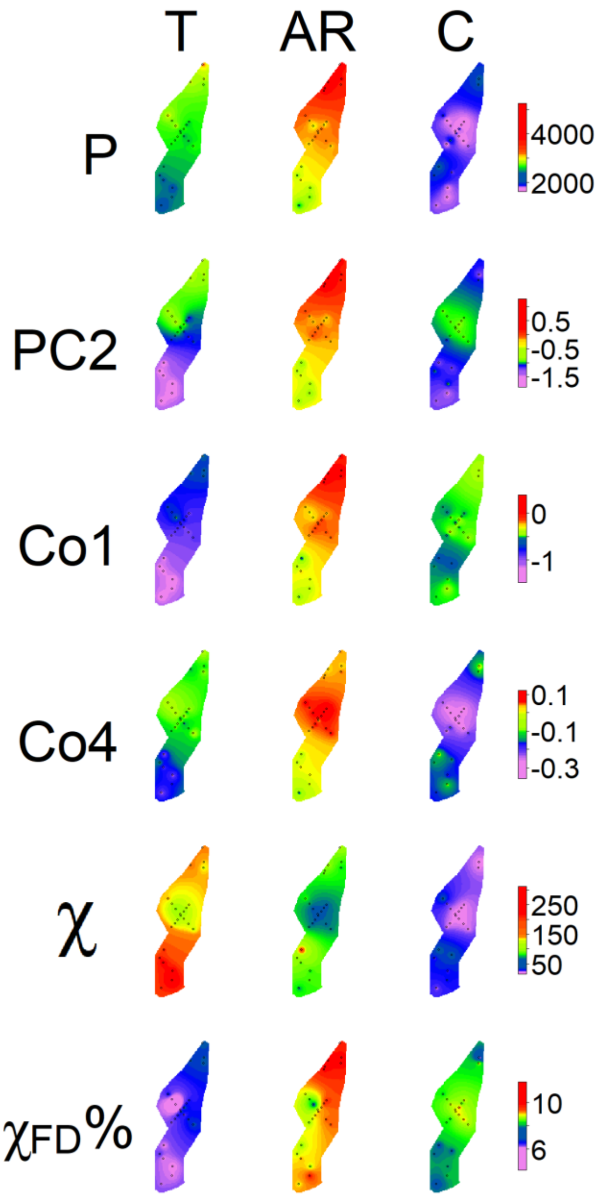

Figure. 6. Interpolated maps of elemental content (weight ppm) in three main stratigraphic levels. The stratigraphic levels are: “T” for topsoil, “AR” for archaeological layers, “C” for C horizon.

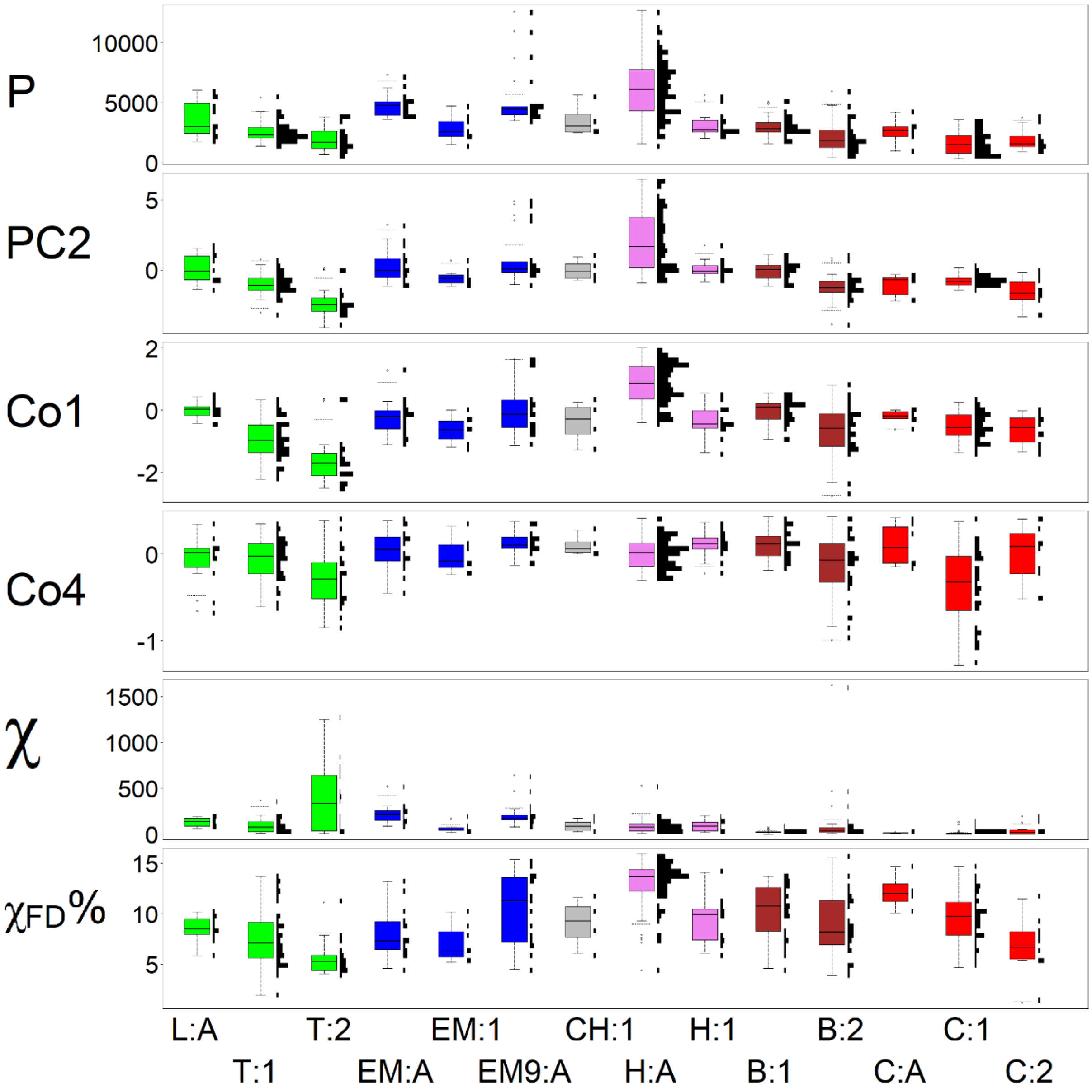

Figure. 7. Boxplots and histograms of elemental content (weight ppm) in categories combining area and dating levels. The categories are ordered primarily by depth / chronological order ("L" for levelling, "T" for topsoil, "EM" for Early Medieval, "EM9" for Early Medieval 9th century, "CH" for charcoal layer, "H" for Hallstatt, "B" for B horizon, "C" for C horizon) and then by the hillfort areas ("A" for acropolis, "1" for 1st bailey, "2" for 2nd bailey).

Multivariate analysis

Principle component analysis performed on elemental content data (described as PCA and its components as PC1) and the version performed on data after ilr-transformation (described as PCAilr and its components as Comp1) revealed interesting patterns. Here we present and comment only first five components, as they explain majority of variability, the results for all components including tables and figures are in Supplementary materials 12–19). First component PC1 explained over 43 % of variability. It was connected to Al, Si, K, Ti, Rb and Zr positively and to Mn, Fe, Cu, Zn, As, Pb negatively. According to boxplots representation, the most outstanding pattern was connected to negative values manifested in topsoil of 2nd bailey (categories "T" and "2"). Positive values tended to be connected to archaeological layers and C horizon, mainly in 1st bailey (categories "AR", "C", "1"). Component PC2 explained over 24 % of variability and was connected to P, Mn, Cu, Zn and Sr positively and to As and Pb negatively. Boxplot representation showed that this component was very well linked to archaeological layers (scores higher than −0.89, except B horizon in 2nd bailey, category "B: 2"), and to C horizon (scores lower than 0.15). Component PC3 explained over 11 % of variability and was connected to Fe, As, Pb positively and to LE negatively. High positive values were manifested only in topsoil of 1st bailey and topsoil and B horizon of the 2nd bailey (categories "T: 1", "T: 2", "B: 2"). Interpolation showed positive values also in archaeological layers in 1st bailey. Component PC4 explained over 7 % of variability and was linked to Al positively and Zr negatively. The most distinctive pattern of this component was manifestation of positive values in C horizon. Component PC5 explained over 5 % of variability and was connected to Si negatively and to Fe and Rb positively. Boxplots representation showed that positive values were linked mainly to C horizon in all areas, while topsoil categories and archaeological layers were like each other. The results of PCAilr were oriented mainly on P, Mn, Cu, Zn, As and Pb, Results for first five components are in Table. 7 and Figure. 15 for maps and Figure. 16 for boxplots. First component (Comp1) explained over 61 % of variability and was linked positively to P and Mn (mainly archaeological layers, distinctively manifested in Hallstatt layers of acropolis, "H: A" category) and negatively to As and Pb (manifested mainly in topsoil of 1st and 2nd bailey, categories ("T: 1", "T: 2"). Component Comp2 explained over 27 % of variability. It was connected negatively to Si, K and Zr, and positively to P, Mn, Zn and Pb. Boxplot representation showed continuous increase of values along stratigraphical gradient from

C horizon (lowest) through Hallstatt and layers dated to Early Medieval to topsoil layers (highest). Component Comp3 explained over 4 % of variability. It was connected positively to P and negatively to Mn. The boxplot representation showed that topsoil samples were influenced by both positive and negative values similarly. Archaeological layers too, with diversity found in cases of B horizons in 1st and 2nd bailey (categories “B:1”, “B:2”), where great ranges of values were also found. The charcoal and Hallstatt layer in 1st bailey (categories “CH: 1”, “H: 1”) were the only categories almost avoiding positive values. The diversity was also observed between C horizons in acropolis and first bailey (categories “C: A”, “C: 1”). Component Comp4 explained over 2 % of variability and was connected to P (positively) and to Cu, Zn and Sr negatively. Boxplot representation showed interesting pattern with all categories reaching maximal values at same level, thus containing diversity only by negative values. The low values were reached in all topsoil categories, in B horizon of 2nd bailey (“B:2”), and in C horizon of the 1st bailey (“C:1”). Component Comp5 explained over 1 % of variability. It was connected to “As” (positively) and to Sr and Pb (negatively). Boxplot representation showed slight difference between archaeological layers from acropolis and 1st bailey. Spatial interpolation found distinctive spatial diversity in area of the 2nd bailey.

Magnetic susceptibility

The results of mass-specific magnetic susceptibility (χ) and its frequency dependence (χFD%) are presented in (Supplementary material 4). The χ values ranged between ca 5.3 and 1620.7 ($\times 10^{-8}$ m^3 /kg) and χFD% values from 1.2 % to 15.9 %. The spatial distribution of the magnetic parameters and boxplot representation shows large diversity among topsoil, archaeological and C horizon stratigraphic contexts. The highest χ values were recorded in 2nd bailey in topsoil (category “T: 2”). The topsoil of 2nd bailey is highly influenced by the recent forest vegetation. In the litter and Ah horizon ferrimagnetic fly ash particles are accumulated mainly due to atmospheric deposition. They are most probably derived from recent industrial activities (coal combustion) in Ostrava and Katowice power plants (Heller et al., 1998). One can imagine that fly ash particles were distributed on the whole investigated area, but as acropolis and 1st bailey has grass vegetation, particles can migrate down along the profile while at 2nd bailey fly ash may be concentrated in the soil litter (Jordanova et al., 2008). Early medieval layers at acropolis contain according to micromorphological evidence commonly the daub and charcoal fragments, which contribute to increase of χ. of daub fragments is always higher than sediment (in B and C layers), because archaeological layer was certainly affected by fire create ferrimagnetic minerals as magnetite and maghemite (Tite and Mullins, 1971). The lowest χ values were recorded in early medieval layer and B horizon from 1st bailey ("EM: 1", "B: 1"), and in C horizons of acropolis and 1st bailey ("C: A", "C: 1") despite the fact, that B horizon of the 1st bailey contained in micromorphological reference the relicts of daub quite commonly. On the other hand, it may be just local exception. The highest χFD% values (pedogenic fraction) were determined at acropolis in the EM9, H and C subcategories. The lowest χFD% was determined at 2nd bailey in topsoil and C-horizon (subcategories T2 and CL2). Low χFD% can be explained by the called masking effect, because high content of coarse-grained anthropogenic ferrimagnetic particles obstructs the identification of pedogenic fraction (Szuszkiewicz et al., 2021). The interpolation of these results calculated by Spearman correlation (Table. 9) has brought these patterns: The χ shows strong positive correlations with Mn, Cu, Zn and Pb, Comp 2 and "visually" – with PC3 (which show positive correlation with Fe, As, and Pb). The χFD% exhibits strong correlation with the P, Sr, Comp 1, (which is positively linked to P and Mn) and to PC2 (which make links to P, Mn, Cu, Zn, Sr). This is good indicator of archaeological layers distinctively manifested in Hallstatt layers of acropolis, "H: A" category, because is extremely rich in phosphate and Fe/Mn nodules as revealed from micromorphology.

Discussion

Multivariate analyses and pXRF elemental content

The results showed that geochemical record of soil record at Chotěbuz-Podobora hillfort was quite usual: we have found strong distinction between elements usually connected and interpreted as anthropological indicators (P, Mn, Sr, Cu, Zn) (e.g., Horák et al., 2018; Šmejda et al., 2018) and elements interpreted as those derived from natural environment (Si, Al, Rb, Zr) (Horák et al., 2018; Janovský et al., 2020a,b). There was also distinction of elements which can be interpreted as connected to recent anthropogenic sources (As, Pb, as found in Horák and Klír, 2017). The elemental composition of the main stratigraphic categories was a bit mixed between typical human indicators (P) and natural elements (Si), as was also found in similar context (Danielisová et al., 2022). Nevertheless, such mixing was well diversified by multivariate analyses in the Chotěbuz-Podobora dataset. Therefore, the interpretation was that there is strong and well distinguishable anthropogenic signal on the hillfort connected mainly to P and Mn, and to Cu and Zn. As revealed from the micromorphological results, mainly layers related to Hallstatt period and 9th century occupation are extremely rich of phosphatic pedo-features and presence of bones and burned bones. These features give the soil the strong phosphorus signal. All archaeological layers show the high dependence on oxidation/reduction processes with the development of Fe/Mn nodules, so the increased values of Mn are quite predictable. The geochemistry was also influenced by (potentially) recent deposition by As and Pb. Such pollution was identified previously also in the alluvial plain of nearby river (Faměra et al., 2018). Based on the connection to specific elements and also to areas and sediments of anthropogenic influence, we interpreted these signals as anthropogenic: negative values of PC1 (probably recent), positive values of PC2 (archaeological signal), positive values of PC3 (probably recent), positive values of Comp1 (archaeological signal), negative values of Comp1 (probably recent), positive values of Comp2, negative values of Comp3 (distinguishing between anthropogenic Mn and natural P), positive values of Comp4 (P), negative values of Comp5 (Pb and Sr, whereas positive values represent natural aspect of As). The analyses show usual ways of distinguishing anthropological and natural signals: whereas traditional PCA performed on elemental content showed distinction between main categories of signals (natural vs archaeological vs recent anthropogenic), the PCA on ilr-transformed data (respecting compositional character of geochemical data) focuses on elements with more variability (usually anthropogenic indicators) and therefore distinguishing more the diversified aspects of anthropogenic signals. Further, we would like to emphasis some specific patterns directly: 1) Generally, the main difference in archaeological layers was between areas of acropolis and 1st bailey, not among the chronological categories. Such example can be stated for a distinction between early medieval layers from acropolis (“EM: A”, “EM9: A”) and from the 1st bailey (category “EM: 1”). This was observed in case of most of elements except of As, Sr, Pb and LE; in cases of PC1 to PC4 (not in PC5) and in case of Comp2. This shows that although historical context can change, the activities were performed in the context of the site – which apparently retained throughout the centuries and the space was used in similar manners in Hallstatt and Early Medieval periods. 2) There were indications, that some categories as described probably mixed real categories. The most distinctive example was the similarity of H: 1 and B:1 signal often connected with multimodality of H: 1 data in cases of PC2 or Comp1. That would mean, that some samples although categorized based on archaeological knowledge of the site and macroscopic observation should be labelled by another category (i. e geochemical signals identify such layers / materials differently). This shows the potential of pXRF to be used on methodical level to better distinguish between descriptive categories. Bimodality and / or multimodality was also found in cases of Rb content, scores of PC1, PC5, Comp1 and Comp2. Similarly, some of the signals were very distinctive in defining the categories and thus being the "thing", which archaeologists usually want to use in geochemistry: find a "typical signal for something". Examples of this could be: PC4 distinguished EM A from EM 1; Comp1 distinguished H: A very well; Comp2 showed decrease in chronology (highest values in latest layers vs lowest in oldest); PC2 strictly defined what is or is not archaeological signal. But the important finding in this way, that in such way usually work only results of multivariate analyses and not elemental contents. Therefore, such using is strictly site specific and can be used after substantial amount of data are analyzed. 3) There were also patterns in interpolations indicating spatial diversity inside areas (not between areas as it was already mentioned, and it was also basically recorded in all cases). Indications of intra-areal spatial diversity were found in cases of PC1, C3, PC4; Comp1 and Comp3, but basically not in the cases of elemental content (there, only between areal diversity was observed). Therefore, we can see that spatial distribution of the archaeological activities can influence the spatial distribution of soil characteristics, but again, this was revealed mainly in the results of multivariate analyses.

What extent of waste could affect the geochemical composition of soils?

Archaeological Dark Earth soils belong into the category of anthrosols. These soils are human influenced and typical mainly by the higher content of nutrients and organic matter. The formation of these soils could happen on Acrisols, Arenosols, Cambisols, Ferralsols, Latosols, Luvisols, Nitisols, and Podzols (Macphail and Courty, 1985; FAO, 2008; Motsara and Roy, 2008; Macphail et al., 2003; FAO, 2021). The appearance of these soils (ADE) is associated with the obligatory deposition of organic and inorganic waste, as well as deliberate modifications to improve home grasslands and crop fields or repeated destruction of forts during medieval warfare, including the burning of ramparts and settlement timbers, wattle and thatched houses, crops, and wooden tools, all of which could result in charcoal in the soil. Typical properties of soils at hillfort were firmly usual, which was strong bond between the measured elements and defined human influenced factors such as phosphorous, manganese, strontium, copper and zinc. The results of analysis were mainly oriented on P, Mn, Cu, Zn, As and Pb elements. Based on the analysis 5 category were distinguished in the area. First category explained the most variability and was linked positively to phosphorous and manganese elements at archaeological layers, as Hallstatt layers of acropolis, and negatively to As and Pb elements in the top soils of 1st and 2nd bailey. Second component discovered around half percentages of variability which was connected negatively to Si, K and Zr, and positively to P, Mn, Zn and Pb (Horák et al., 2018; Janovský et al., 2020a,b). The data represented continuous increase of values along stratigraphical gradient from C horizon through Hallstatt and early medieval layers to topsoil layers. The third variety of analysis was connected positively to P and negatively to Mn which both topsoil samples and archaeological layers (1st and 2nd bailey) were influenced by both positive and negative values similarly. The fourth and fifth components explained less variety which was connected to P and As positively, respectively and to Cu, Zn and Sr at fourth and Sr and Pb at fifth negatively.

Does the soil record differ over the time and space of Chotěbuz-Podobora hillfort?

Most archaeological contexts are located within the soil. Hence, processes of soil formation and soil geomorphology (FAO, 2008; Motsara and Roy, 2008; Devos et al., 2011; Soil Survey Staff, 2014; FAO, 2021) recreate an important function in the archive of history. These processes have substances for the ways of monitoring, recording, understanding, and interpreting these contexts. As revealed from the combination of different methodological approaches, the single approach to understand the soil formation processes may be misleading. For examples we were able to realise from the geomorphology acropolis studied during long term archaeological research, that the original surface of acropolis as under the slope. The micromorphological analyses of Hallstatt horizons revealed that all those layers are redeposited on the slope without any signs of bioturbation, so the sloping was quite quick and repeating. The micromorphology also revealed that the material of Hallstatt horizon is extremely rich of phosphates hidden in bones, burned bones and phosphatic accumulations/nodules. This finding nicely explains the extremely increased values of P by pXRF (Horák et al., 2018; Janovský et al., 2020a,b), but according to the internal structure of the sediment one could say, that these values doesn't reflect the intensity of pedology, but simply the presence of degraded bones. Another methodological approach we used, the frequency depended magnetic susceptibility on the other hand confirmed, that the magnetic signal clearly confirms high intensity of pedological processes. This means, that Hallstatt horizon buried at acropolis has on one side the signs of redeposited cultural layer (confirmed by geomorphology, micromorphology and geochemistry) and on the other hand also the properties of well-developed soil (confirmed by magnetic studies as well as by geochemistry). The final scenario interpretation may be as follow: During the Hallstatt occupation developed at the site soil which was highly influenced by human action and by pedological processes. Later, the soil was repeatedly eroded and accumulated at the bottom parts of the slope and was lately buried by horizon developed in 9th century occupation. The 9th century occupation seems to be different story from the point of formation processes. While the micromorphological properties show soil rich of organic matter, phosphate, Fe/Mn nodules and high bioturbation, the other proxies get by XRF, and magnetic studies are less extreme than in case of Hallstatt layers. The soil properties at acropolis differs over the time a lot. The reason is, that those horizons were formed in different conditions and the material used has different provenance also. While the lower parts of the profiles are represented by colluviated soil rich of phosphates and organic matter, the upper parts were accumulated quite quickly mainly from the destruction of objects constructed at acropolis. The result is unsorted soil with lower number of anthropic elements. On the other hand, the presence of daub it the reason why magnetic susceptibility enhancement is nicely visible there. It can be also said that there are big differences between the soils of acropolis, 1st and 2nd bailey, not only because these differences are clearly visible today. These spaces were obviously used in the past by different way (see the chapter 2), which influenced the development of different properties of soils. The original surface of the 1st and 2nd bailey had to be flat, because none of studied horizons doesn't show any sign of slope processes. What is typical for Hallstatt layers in all three parts of the hillfort is intensive depletion of soil and simultaneously the origin of Fe/Mn nodules. This fact is probably influenced by the clayey and therefore water holding geological substrate, but it intensively influences the property of the soil and for sure it influenced the living environment in that time. The intensity of human influence is always marked by the presence of charred organic matter. While the Hallstatt horizons at acropolis are rich of phosphate, the phosphates are at 1st and 2nd bailey nearly missing as confirmed by micromorphology as well as by geochemistry. Surprisingly, during the processing of the chatted organic matter the soil was not influenced by high temperature, because the enhancement of magnetic susceptibility doesn't reflect it. The black layer at 1st bailey can be used as a marker, because it is continuous all over this area. At first it was thought that the layer is composed mainly of charred material but as confirmed from the micromorphology, it doesn't contain more charred organic matter than the layers above or below. The typical color of the layer is made of limonite. This was also the reason why there was not visible enhancement of magnetic signal in this layer. Contrary to it, the magnetic signal is enhanced in the layers above, and the reason is, that those layers contain the fragments of daub not visible by naked eye. The presence of limonite may relate to some metallurgic procession in the 1st bailey.

How the refuse management influence the properties of soils?

Past human activities could be related to the accumulation of some archaeological elements like P, Ca, Mn, K, Fe, Zn and Cu in soils (Fernández et al., 2002; Šmejda et al., 2017) which could result soil like anthrosols by a period and intensive activities. The activities could contain prescribed burning of forests, animal husbandry, domestic waste disposal etc. The settlement activities created some chemical signatures which was specific for the site because of combined features of soil forming factors and processes, site- use history and geology substrate. One of the examples of refuse management may be linked with the Hallstatt occupation of acropolis. During the occupation was the refuse dumped on the surface and intercorporate into the soil. The result is intensive pedogenesis detected by frequency dependent susceptibility. It could be clear that people may transport material down the slope to clean the acropolis surface, and to make its surface flatter. But this is not the case, the Hallstatt horizon accumulated at one site of acropolis was accumulated naturally, probably after the abandonment of the site, because those microlayers don't seem to be trampled or dumped. The second example of the refuse management is the 9th century at 1st bailey. It was thought that the black layer is kind of refuse rich of charcoal, may relate to the metallurgic management. We realized, that the layer has color due to the presence of limonite, not due to the presence of charred material. It may relate to the refuse, but more likely is the color of the layer related to the post depositional processes. All over the refuse management influence the properties of soils significantly. It is nicely visible that most medieval layers are composed by the material from the object destruction, i.e., there was possible to detect nicely by the magnetic properties and by micromorphology the presence of daub as well as the presence of rock fragments not related to the local geological substrate.

Conclusion

The vast majority of the archaeological record is in one way or another part of the soil and therefore affected by soil processes that rework the remains of past human activities studied by archaeologists. During all our interventions into the subsurface archaeologists constantly observe soils though we rarely see them and record them as such, which may have negative consequences for our understanding of the contexts we observe. The study showed several important and interesting results. One of them is the general observation on problematic of soil record in archaeological contexts. So far there doesn't exist the exact terminology for soils influenced in past by human action in different intensity and consequences. The differences between terms like cultural layer or Anthrosols or Dark Earth are often used as synonyms, without explanation of detail formation processes. The distribution and interpretation of variable geochemical composition of soil record was one of the main goals of the paper. The soil record detected at the site contained high amount of phosphorus, even higher than usually recorded at abandoned medieval villages. Based on areal and stratigraphic distribution were discovered three groups of elements: 1) elements with maxima in “Archaeology” category (Si, P, Ti, Mn, Sr, Zr); 2) elements with maxima in “Topsoil” category (Cu, Zn, As, Pb, LE and Fe, Mn partially); 3) elements with maxima in “C” category (Al, K, Rb and partially Fe). The statistic evaluation of given data helped to understand the dependence between different components. Component PC1 explained over 43 % of variability which was positively connected to Al, Si, K, Ti, Rb, and Zr and negatively to Mn, Fe, Cu, Zn, As, Pb. The most outstanding pattern was connected to negative values manifested in topsoil of second bailey, and the positive values tended to be connected to archaeological layers and C horizon, mainly in 1st bailey. Results of component PC2 were connected to P, Mn, Cu, Zn and Sr positively and to As and Pb negatively. This component was very well linked to archaeological layers and to C horizon. Results of component PC3 was connected to Fe, As, Pb positively and to LE negatively. High positive values were manifested only in topsoil of 1st bailey and topsoil and B horizon of the 2nd bailey. Results of component PC4 were linked to Al positively and Zr negatively. The most distinctive pattern of this component was contained the positive values in C horizon. Results of component PC5 results were connected to Si negatively and to Fe and Rb positively (linked to C horizon). The magnetic properties combined with the micromorphology as the additional proxies helping to characterize the soil and its formation processes showed to be very useful. The values of magnetic susceptibility (χ) increased mainly in the topsoil of 2nd bailey. The reason is the ash deposition combined with the presence of forest recently covering the area. The values of samples coming from 1st bailey were distinctively lower. Frequency dependent susceptibility (χFD%) reached the highest values in the archaeological layer with spatial diversity in 1st and 2nd baileys. The combination with the micromophological observations showed, that there are clear signs of redeposition with missing bioturbation and therefore soil record with the high χFD% values within the Hallstatt horizon at acropolis is redeposited soil, not only redeposited dumping. The micromorphology also revealed that the material of Hallstatt horizon is extremely rich of phosphates hidden in bones, burned bones and phosphatic accumulations/nodules which significantly influenced the soil composition. Finally, all these observations helped to unlock the formation processes at the site. The oldest human presence is attested by the development of soil reflecting the presence of organic residues. After the first abandonment of the site at the end of Hallstatt period was the organic rich horizon eroded and accumulated at one side of the acropolis. The surface of the acropolis became flatter and levelled. The soil development in the medieval period was highly influenced by an aggradation of material originally used for different types of building constructions. The presence of anthropogenic elements reflects in that time not only the deposition of organic matter but also the deposition of ash. While the acropolis was heavily occupied, and its geomorphology dramatically changed over time, the 1st bailey served mainly as a production space. The function of the 2nd bailey stays unsolved due to its poor preservation. The most recent human influence in the soil record is visible in the topsoil; first as the result of agricultural practices and second as the contamination by Pb and magnetic particles resulting from the atmospheric pollution. The soil record at archaeological sites differs significantly not only over the time, but also regionally. The reason is original geomorphology, use of the space in the past during the settling as well as in recent times and availability to the recent pollution. The refuse management influence significantly the properties of soils and it is well detectable in Hallstatt horizons as well as in medieval horizons.

5.3. The Influence of Ant Activity on Soil Dynamics at an Archaeological Site, case: Oppidum Bibracte

Bioturbation stands as a fundamental soil formation process, and extensive research has investigated its impact on soil morphology and development (McKey, 2022). Soil fauna activities play a significant role in global terrestrial bioturbation, influencing the distribution of soil particles, arrangement of soil layers, blending of mineral and organic materials, thereby affecting soil properties (Kristiansen et al., 2001). However, the capacity of soil fauna to disturb archaeological records or even imitate human-made structures is profound and extensively documented (McKey, 2022; Venn, 2015). Such occurrences at archaeological sites can considerably complicate archaeological interpretations (Eldridge and Myers, 2001; Rink et al., 2013). Ants enhance soil aeration by forming macropores, thereby accelerating water infiltration rates and impacting nutrient dispersion (Evans et al., 2011; Frouz and Jílková, 2008). This activity also contributes to enhancing soil fertility. Through the construction of both vertical and lateral galleries, ants wield significant influence on soils to a depth of approximately 150–200 cm, leading to modifications in the physical, chemical, and biological attributes of the soil (Mikheyev and Tschinkel, 2004).

5.4. The influence of ants on soil microstructure

The impact of ants on the soil environment, both within and outside their nests, is widely acknowledged. Their influence on the soil ecosystem encompasses structural modifications and nutrient accumulation (Dostál et al., 2005; Jurgensen et al., 2008; Nkem et al., 2000). Ant activity often leads to the accumulation of organic matter and organo-mineral particles, subsequently followed by the bioturbation of the degraded material. During bioturbation, various ant species and environmental factors determine the mixing of organic and organo-mineral particles with the mineral matrix in distinct ways (Frouz and Jílková, 2008). Interestingly, micromorphological investigations of these processes are relatively limited compared to studies involving other forms of soil macrofauna (Kooistra and Pulleman, 2010; Cosarinsky et al., 2020).

We recorded the below-ground structures of recent and former ant heap and soil in a close vicinity of the recent AH. These soils were influenced by the activities of *Formica* s. str ants (Figure. 4). Our micromorphological observations showed that the internal structure of the recent AH comprised horizons differing in mineral content, element content, intensity of organic matter degradation and, especially, in presence of different sizes of granules. These microstructures apparently originated from excavation and nest building activities of this ant species. Specifically, the layers with more degraded organic matter are characterised by high abundance of microgranules, and those with less degraded organic matter are characterised by presence of bigger granules. This aggregation occurs during the mound building process, especially when the soil is moist, or when it has already been aggregated through the activity of soil organisms, including the ants themselves, e.g., when the ants use their saliva to bind soil particles together to create stable tunnels and galleries (Petal, 1978). We can speculate that the microgranulae were created by the subsequent breakdown of tunnel and galleries walls after the nest abandonment.

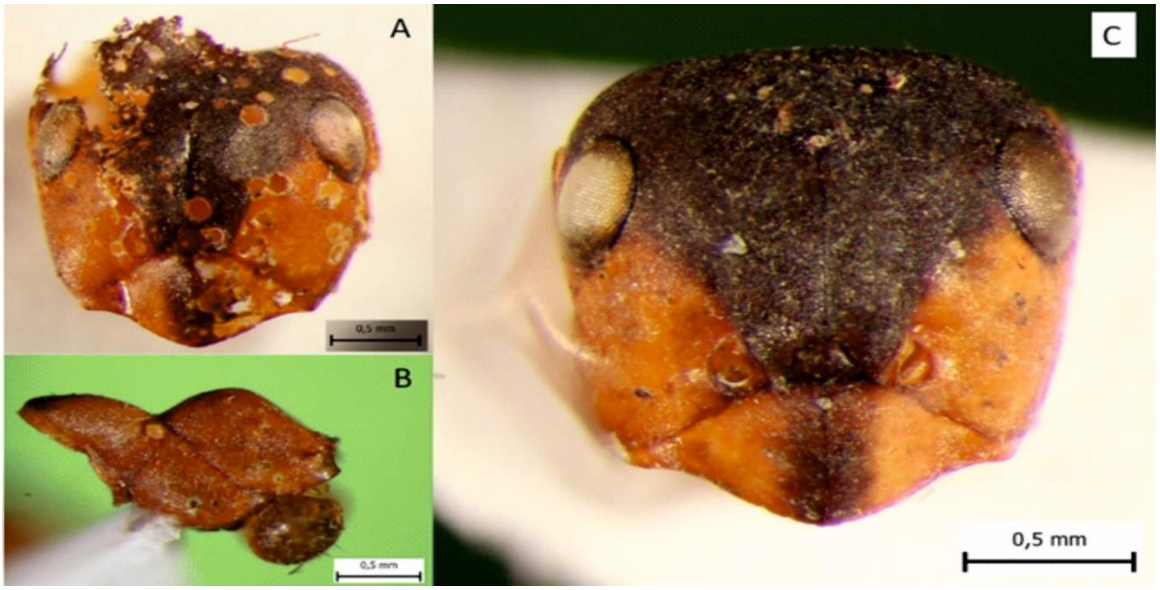

Figure. 4. Ant head capsule of Formica s. str. in frontal view with visible signs of invertebrate-caused decomposition (A). Part of thorax in lateral view (B) and a head capsule with missing mandibles and antennae (C) retrieved from “recent AH”.

5.5. Geochemical and magnetic signals produced by ant activity

Prior researchers have documented elevated levels of carbon (C) and phosphorus (P) within ant nests compared to adjacent soils (Farji-Brenner and Werenkraut, 2017; Frouz et al., 2005). This increase in nutrient content is attributed to the accumulation of plant material used for nest construction, prey storage, and ant feces deposition. Typically, the center of ant nests exhibits the highest P concentrations, accompanied by micromorphological evidence of decomposed and partially decomposed organic matter, along with a distinctive granular microstructure. Since the central area of the nest serves as the primary hub of nesting activity, elevated P levels are expected. Conversely, Formica s. str. ants tend to introduce mineral soil into the mound profile (and older nests may even distribute it outside the mound), potentially diluting the overall nutrient content within the nest (Frouz and Jílková, 2008). In fact, the dilution effect, resulting from the mixing of P, S, and total organic carbon (TOC)-rich organic materials like spruce needles, food remnants, and feces with the mineral soil horizon, might be one reason why the current nest did not exhibit higher concentrations of calcium (Ca), magnesium (Mg), iron (Fe), and manganese (Mn). Given that F. polyctena can contribute annual pine needle input to the nest profile, accounting for 12–37% of the total nest volume (Pokaryhevskij, 1981), this dilution influence likely plays a pivotal role in the overall nest chemistry. While elevated levels of mercury (Hg) and lead (Pb) are often interpreted as soil contamination indicators, these proxies are also influenced by the presence of organic matter (Ballabio et al., 2021). The parent material of the studied site contains abundant Hg, Pb, and Th elements (Gourault, 1999). However, it is plausible that ants transport lithogenic particles rich in these elements into the mound profile during the excavation of underground tunnels and chambers. Consequently, ants have the capacity to augment both the quantity and distribution of these elements within the soil profile. The impact of ant activity on the formation of iron-oxide minerals and, consequently, the measurement of magnetic susceptibility (χ), has not been extensively investigated. In this study, characterizing the AH sediment was more intricate due to its location within an archaeological site. Generally, frequency-dependent magnetic susceptibility (χFD%) displayed elevated values across all studied soils up to a depth of 40 cm, yet only AH soils exhibited heightened magnetic susceptibility (χ) in comparison to the Reference Soil. The "former AH" section comprises a cultural layer, with its lower portion composed of the geological substrate. Magnetic properties effectively mirror these features. The cultural layer demonstrates the highest χ values among all the investigated soils, likely due to its enrichment with micro-remains of ceramics and other burnt materials. This material also displays the highest χFD% values among all the investigated soil sections. χFD% starts decreasing with depth beneath this cultural layer. The geological substrate shows relatively low χ and decreasing χFD%, reflecting a lower content of pedogenic grains towards the section's base and poor magnetic lithology. The Reference Soil exhibits the lowest χ, yet possesses high χFD% values, akin to the investigated AH soils. This observation suggests that AH soils contain a greater proportion of fine-grained ferrimagnetic particles, while reference soils contain a higher content of low-magnetic material (including needles).

6. Discussion

Discussions of offered results of the research and comments on the results are given in the following subchapters. The first subchapter discusses research on long-term inhabited villages from the late iron ages, Hallstatt period and the Slavic period. The sites were conserved over time which enabled to compare their geochemical reflection on a land-use basis. In this part will be description of the methods, due to the fact that the intensity of human impact and pedological processes, and the types of formation processes were not clear macroscopically so we employed different techniques to determine the data. The second subchapter deals with the pedology part of the sites and the methods which used in the research. The third subchapter discusses the geochemical signal of anthropogenic soils which can reflect reflects past settlement activities.
The last subchapter dicusse about How to identify AH structures in soils, andi which way ants can influence archaeological interpretations.

6.1. Studied sites

For our studies some sites were selected. The locality of Chotěbuz and Pilsen were located in Czech Republic, and the location of Bibracte is Located in France. The Chotěbuz site were studies in three parts as Acropolis, first bailey and second bailey. The second site late Iron Age oppidum Bibracte on Mont Beuvray which 7 trenches and profile such as Le Porrey, Le Verger, Le Champlain, La Chaume, La Terrasse, Parc aux Chevaux (PC), and La Braconne were studies in this site. During last five years, the area of Bibracte oppidum was accessible in several trenches and profiles covering sediments with different formation history. In majority of profiles layers was difficult to distinguish phases of natural deposition vs. phases influenced by human activity. For the further research is essential to solve the problem of the sedimentary formation, therefore, we decided to sample in detail set of sections in the profiles and trenches where the origin of large sedimentary bodies was clear. Late Iron Age oppidum Bibracte as a hill-top site on Mont Beuvray as founded at the end of 2nd century BCE and initially consisted of wooden buildings which were replaced by stone structures in the second half of the 1st century BCE. These modifications in the architecture (and in material culture) reflect the political and cultural shifts that took place after the Gallic Wars (cf. Caesar, 1917), connected with Romanization of the Gaul (Luginbühl et al., 2014; Szabó et al., 2019). Apart from public and private buildings, workshops producing metal artefacts were scattered throughout the area of oppidum (Dhennequin et al., 2008).

The oppidum was surrounded by two systems of fortifications (construction type *murus gallicus*): an outer rampart system was 7 km long, that was abandoned at the beginning of 1st century BCE and ideal for inner rampart system 5.2 km long, enclosing the area of 135 ha. Less impressive enclosure systems are still visible *intra muros*, surrounding the summits of Le Porrey and La Terrasse. In the first century BCE, Bibracte reached its peak, shortly before its rapid abandonment after the beginning of the first century AD in favor of a new city, Augustodunum (Barral and Nouvel, 2012), and was never fully populated again. During the Medieval period, a monastery was built in the center of the area enclosed by ramparts (Beck and Saint-JeanVitus, 2018), and the 700 m distant hilltop plateau of La Chaume was regularly used only as a site for annual markets. Recently, mining activities were discovered in the oppidum; these were abandoned at the latest during the 1st century BCE (Guichard et al., 2018). So far, no strong proofs of agricultural activities (cultivation of crops, intense cattle breeding) exist for the area *intra muros* from 2nd to 1st century BCE (Goláňová et al., 2020), with slightly different picture for the Medieval and recent past (Beck and Saint-Jean Vitus, 2018).

Hillfort in Chotěbuz-Podobora consists of three fortified parts – acropolis, 1st, and 2nd bailey which in the past was occupied in two main phases. The first phase is represented by Hallstatt period and the second one by Slavic period. The long-term anthropogenic impact on this area formed not only soil record but also influenced significantly the recent morphology. While the surface of the 1st and 2nd bailey is naturally flat, the surface of the acropolis was originally under the slope. This fact resulted into the accumulation of the thick cultural layer, reaching more than 1.5 m on the north-western part of the acropolis. The geological substrate of the hillfort is built of rocks of the Silesian unit of the Carpathian mantle typical by alternating sandstones and claystones.

The prehistoric settlement of the locality was associated with the Lusatian culture, and its heyday falls in the Early Iron Age. According to this breakdown, we place the beginning of settlement of the hillfort at the end of the Bronze Age (Ha B2-3), the greatest flourishing is observed in the earlier Iron Age (Ha D), and it was inhabited to a limited extent even at the beginning of the Late Period (Lt A). First phase of hillfort occupation is concerned mainly in the northern part of the acropolis. The remains of a light fence were discovered under the body of the wall separating the acropolis from the 1st bailey. It can be dated to the end of the Ha C1a or at the beginning of the Ha C1b. Acropolis was permanently inhabited, and the area was intensively used until the end of the prehistoric phase. This is evidenced not only by the thickness of the cultural layer, but also by its very intense saturation with macro-remains of plants and animal bones. Significant traces of settlement were also documented in the area of the 2nd bailey. In all probes, both the cultural layer and objects that can be associated with the Hallstatt period were recorded.
The occupation intensity of the 2nd bailey seems less significant for Slavic period, but whole part has been used since the beginning of Slavic settlement, as evidenced by both the finds of pottery and objects of an exceptional nature. During the 9th century, the construction of the fortification began, but was never completed. Research with a metal detector then revealed numerous findings of slag, which, however, could be related to both the older (9th century) and younger (2nd half of the 10th century – 1st half of the 11th century) phases of Slavic settlement. The situation at the acropolis was quite complex and the sedimentary record differs according to the position. The archaeological excavations which were done there just a few years ago gave possibility to control the sedimentary record from cores with the archaeological documentation done. The natural morphology of the 1st bailey is flat, and the thickness is constant there. Therefore, we used cross sampling of whole area. The 2nd bailey is heavily turbated and the archaeological situation there is not very clear. The sampling strategy was to cover the general information from the site and therefore the cores were positioned in places where the historical sediments and layers are intact and well known and documented from previous archaeological research. For the study of the sites, we usedsome analysis such soil micromorphology, Portable X-ray fluorescence (pXRF), magnetic properties, Principal components analysis, and Optically Stimulated Luminescence dating which some of them noticed partially.

Soil micromorphology is the study of soil substrate via oriented thin sections. While the analytical method will show the general composition of the soils, the soil micromorphology may reveal much more information related to the primary and post sedimentary formation processes. There was sampled in total 16 small thin section of the diameter 2.5 – 3.5 cm. Material for thin section was taken from the cores at acropolis, 1st as well 2nd bailey from the horizons where any lithological change was visible. The dating of the timespan of accumulation is based on archaeological knowledge of this site. The samples were packed into clink foil and transported to the laboratory, dried and impregnated in vacuum by resin Polylite 2000. After curing thin section of the thickness of 30 µm were done from them. Those sections were studied under the polarizing microscope at the magnifications ranging 16 – 400× and described according to Stoops (2003), Stoops et al. (2010) in Supplementary material 1, 2 and 3.

Portable X-ray fluorescence (pXRF) is a non-destructive analytical technique that provides near-instantaneous elemental analysis of materials. This technique is unique to the elemental composition of the sample. Because each element has its characteristic, and pXRF can tell exactly what elements are in the sample and in what quantity, can be operated in the field anytime (anywhere), and provide fast acquisition of geochemical data for rapid delineation of anomalous zones and the indepth, quantitative analysis of metal content for geochemical mapping. (Potts et al., 1997; Kalnicky and Singhvi, 2001; Markowicz and Van Grieken, 2002; Sitko, 2009).

The magnetic properties of the soil minerals depend essentially on the Fe content, because Fe is 40 times more abundant than the sum of all other magnetic elements in the earth's crust (Coey, 1987), and Fe-oxides such as magnetite and maghemite are ferrimagnetic (Cornell and Schwertmann, 2003) and can be easily identified due to their very intense response to external magnetic field. Magnetic susceptibility measurements were performed in the Laboratory of Rock-Magnetism in the Institute of Geophysics, Czech Academy of Sciences. Bulk samples were used to measure volume-specific magnetic susceptibility (κ, SI) by using an MFK1-FA Kappabridge device (AGICO, Brno, Czech Republic) (Pokorný et al., 2011). Each sample was measured twice at two operating frequencies, f_1 = 976 Hz and f_3 = 15 616 Hz. Readings of the unconsolidated samples were taken in plastic bags; the measured susceptibility values were normalized by the mass of each sample and expressed as mass-specific magnetic susceptibility [χ, m^3 /kg]. Magnetic susceptibility refers to the concentration, size and character of Fe-oxides minerals, and can be detected even in trace quantities in any rock, soil, or even in organic tissue (Thompson and

Oldfield, 1986). Frequency-dependent magnetic susceptibility, χFD%, is a particular property of ultrafine, superparamagnetic grains, which result from pedogenic processes (Maher, 1986).

6.2. Formation of the soils at the studied sites

Five sedimentary categories based on field observations were divided at oppidum Bibracte: 1) recent soil; 2) cultural layer; 3) anthropogenic colluvium; 4) natural colluvium; and 5) geological substrate. The assignment of individual categories to the sedimentary record was made on the basis of macroscopic observations. Along with the detailed characteristics of individual categories, it is necessary to state the terminological context. For the purposes of this characteristic, general terms have been chosen for several reasons. The division should be as simple as possible in order to be able to perform a comparative PCA analysis and at the same time the terminological scope as general as possible because the more detailed genesis of individual horizons could not always be fully determined. The terms used are often understood more specifically in various fields, so it is stated at the very beginning of their characteristics how the term is understood and used.

Recent soil is defined as humous uppermost A horizon developed due to the soil processes. The specific of Bibracte oppidum is the lack of well differentiated soil horizons, therefore we decided to mark as soil horizon only the uppermost soil horizon corresponding to A horizon. The category "recent soil" is represented by unsorted sediments with the clast content of 1 – 50 cm (60– 70%) and grayish brown (10YR 5/2) to very dark grayish brown (10YR 3/2) moist color.

Cultural layer is in this case defined as layer originated due to the settlement activities. We assume that the layer was formed on site by disposal of settlement waste, homogenization due to settlement activities and bioturbation. The soils at these parts as a macromorphological features had pale yellow (10YR 8/4 to 10YR 7/4) moist color, distinct to smooth distinctness (boundary), unsorted material - dusty sandy sediment with a high content of rock clasts with a size of 1- 10 cm with no signs of rooting, most of the pores were between single aggregates, sandy silt with the presence of rock fragments.

Anthropogenic colluvium is defined as sediment that was formed as a result of gravitation and anthropogenic activity. This category can include both sediment whose part consists directly of anthropogenic waste and sediment which was formed, for example, by erosion caused by man or directly by man's relocation due to some construction activities. The color at anthropogenic sites were black to very grayish brown (10YR 2/1 or 7.5YR N2 to 10YR 3/2) in moist conditions. The distinctness (boundary) between layers at this part were mostly wavy/irregular to convolute. The category "anthropogenic colluvium" is represented by unsorted sediments with the 15 cm thick black layer composed of charcoal. The grain size was responsible for the material with sandy silts with the presence of clasts of between 1 to 2 cm with the percentage of 50 %. The grain size was responds from single grain to blocky structure with rapid to moderate soil infiltration rate, sandy silt texture (macromorphological features).

The term natural colluvium means a type of sediment that originated in a more or less natural way with the main trigger the gravitation. If there was human impact present in the origin of that sediment, then it is not macroscopically obvious, i.e., that the sediment shows no signs of human influence, including artefactual filling. Colluvium is defined as 'a superficial deposit transported predominantly by gravity containing less than 50% of material by for example erosion (Lisá et al., 2022a) of less than 60 mm in size (i.e., cobbles). Colluvium comprises dense material, silty sand with many cobbles and boulders and it was generally located in the lower and middle portions of the study area. The colluvium appears to be intermittent in extent, separated by extensive zones of saprolite and rock outcrop.

Geological substrate is a term which on oppidum Bibracte characterizes the eluvium of the bedrock and does not show signs of displacement. It is mostly a ventilated rock that is disturbed by frost processes, or affected by pedogenic processes. The macroscopical features were brown to dark brown (10YR 5/3 to 10YR 4/3) moist color, occulated to diffuse distinctness (boundary), moderately sorted. Massive structure with very slow infiltration rate. The geological substrate at Bibracte were contain rhyolite mostly, which was affected by permafrost.

The pedological description of the cores from Chotěbuz brings important information about the nature of the soil record. During the description the main aim is concerned to the color, and some other pedological properties. The color of sediments was identified in both wet and dry states using a Munsell soil color chart. Soil color and other factors containing texture, structure, and consistency have been used to determine and specify soil layers and to group soils according to the soil classification system (USDA and Soil Survey Staff, 2010; Liles et al., 2013; Sawada et al., 2013; Soil Survey Staff, 2014). Soil color has been used as one of the key characteristics to determine horizons in a profile and to categorize soil types in a territory. Regular measurement of soil color has often been accomplished in the field by visually comparing a soil sample with the chips of standard color charts (Munsell, 1905).

The sedimentary record of the acropolis varies significantly, because the accumulation of the soil material was influenced by the natural sloping of the site. The thickness of the soil in NW part is much thicker than the soil on E part of acropolis. The soil record in NW part was thicker than on E part of acropolis. Macroscopically was possible to divide minimally 4 layers differing by color from 10YR 3/2, 4/4, 4/6, 3/2, 6/3, 6/4, 3/1, and 6/6 with the texture of clay, clayey silt, and silty clay. The transition between single horizons is always abrupt. Archaeologically is possible to link those layers to the different occupational periods, i. e. horizon accumulated during Hallstatt period, horizon accumulated during 9th century, horizon accumulated during 9th to 10th century, horizon accumulated during 11th century and recently accumulated horizons. Key morphological characteristics of studied soil horizons at acropolis were, easily demarcated, ranging from clear to abrupt with either wavy or smooth horizon topography.

6.3. Geochemical signal of anthropogenic soils

Past human activities could be related to the accumulation of some archaeological elements like phosphorous (P), manganese (Mn), potassium (K), iron (Fe), Zinc (Zn), and copper (Cu) in soils (Šmejda et al., 2017; 2018) which could result in anthropogenic soils like anthrosols after a period of intensive domestic activities. The activities could contain repeated burning of vegetation biomass, conducting animal husbandry, domestic waste disposal etc. The settlement activities created some chemical signatures which were specific for the site because of combined features of soil-forming factors and processes, site-use history and geological substrate. With regards to human impact, the indicators of agro-pastoral activities are very scarce and punctuated throughout prehistory and the Bronze Age (from ca 5 000 to 800 BCE). The oldest traces of occupation of Mont Beuvray date back to the Neolithic period (5th millennium BC; Martineau et al., 2011; Guichard and Paris, 2013). Even after this date, and despite further deforestation phases occurring during the Iron Age (800–50 BC), the classical Middle Ages (around 1000 CE) and the Modern period, woodland remains dominant, and proximal pollen and fungal indicators of human activity are only present in one core, dating to the beginning of the 16th century to the beginning of the 19th century (Jouffroy-Bapicot et al., 2013). The decrease of anthropogenic pollen indicators during the middle Neolithic in some parts of the Morvan coincides with the onset of the Neoglacial, but this trend is not obvious everywhere (Jouffroy-Bapicot et al., 2013). The most obvious climatic change in the Morvan area is the decrease in human activity during the middle Bronze Age connected with a cool and moist phase corresponding to an abandonment of lacustrine habitats in the Jura and the Alps (Magny, 2004; Magny et al., 2009). The vegetation and land-use history of the surroundings of Mont Beuvray are documented by three palaeoecologically studied peat sequences (GrandMontarnu near the Haut-Folin, sources de l'Yonne and Port-desLamberts some 5 km north of Mont Beuvray; Jouffroy- Bapicot et al., 2013) and recently also by two sections in the alluvial zone of small streams close to Mont Beuvray (Petřík et al., 2021). Agro-pastoral indicators, woodland openness and metallic pollution increased in the Late Iron Age (since the 5th century BCE) and reached a maximum during the last two centuries BC (Jouffroy-Bapicot, 2007). This trend was also documented in the aggradation of alluvial deposits around Bibracte (Petřík et al., 2021). Thereafter, agro-pastoral activities in the Haut-Morvan decreased during the Gallo-Roman period, but increased again during the Early Medieval period (5th– 10th century CE). Palynological, archaeological and historical data complement each other, and document the history of the Medieval period and Modern Times (Balland et al., 2019). The study of alluvial deposits in close proximity of Bibracte show that increased sedimentary activity occurred in the High Medieval period and continued until the post-Medieval period (Petřík et al., 2021). The increasing human impact during the Late Iron Age and the Roman period in the Morvan is in keeping with the central European trend, which coincides with a wetter and warmer climate (Büntgen et al., 2011). The impact of the 'Little Ice Age' on the Morvan Massif is not clear, probably mainly because of the specific land use prevalent on the massif at that time. The exploitation of firewood relegates agropastoral activities to a marginal activity (Jouffroy-Bapicot et al., 2013). The Medieval Climate optimum is reflected in the Morvan area by the intense cultivation of chestnut trees on its southern slopes (Jouffroy-Bapicot et al., 2013). Favorable climate conditions may have facilitated this cultivation, which was at the periphery of the known geographic distribution of chestnut production during the late Middle Ages and modern times (Conedera et al., 2009).

Le Porrey site were containing elements like "As, Rb and S" which are typical at Bibracte for colluvial materials- which can be seen at Le Porrey site are colluvial deposits. The research showed that part of La Terrasse, small part of Le Champlain, Le Verger, La Terrasse A, La Chaume and La Braconne (BRAC) were affected by recent soil pedogenesis. This soil has been undisturbed long enough ago to allow for development of a clear topsoil horizon, but not long enough for any differentiation of the subsoil to occur. However, narrow bands of alluvium left by erosion (Lisá et al., 2022a,b) at different times can be seen, especially in the lower depths. Recent soils are usually very fertile and can be used for a wide range of purposes, especially if they are deep and free-draining; the most characteristic elements in this soil type were~~,~~ revealing probably the presence of organic matter.

By the term anthropogenic elements like Th, Sr, K, Sr, Z, Rb, Mn, Cu and P which refer to elements brought along with materials modified by the humans, part of Le Verger, La Champlain, major part of PC2, and part of La Terrasse were affected by human activities and reveal the highest human impact on soil chemistry in comparison with other recognized areas. Part of La Braconne (BRAC), Le Porrey, Le Verger, and Le Champlain was affected by chemical elements like Si, Al, Ti, Ni, Fe and Zn. The La Terrasse sedimentary archives appear to be heavily bioturbated by roots of woody plants. Although the volume of roots (present in dried flot fractions) generally decreases towards the deeper strata (in all but test-pit H), there are exceptions to this rule. The root accumulations in lower strata probably coincide with buried fossil soil horizon(s). Other types of plant macroremains, such as wood charcoal, seeds and fruits fossilized (archaeologies) through charring or seeds fossilized through mineralization, are extremely rare.

At Chotěbuz we have found strong distinction between elements usually connected and interpreted as anthropological indicators (P, Mn, Sr, Cu, Zn) (Horák et al., 2018; Šmejda et al., 2018) and elements interpreted as those derived from natural environment (Si, Al, Rb, Zr) (Horák et al., 2018; Janovský et al., 2020a,b). There was also distinction of elements which can be interpreted as connected to recent anthropogenic sources (As, Pb, as found in Horák and Klír, 2017). The elemental composition of the main stratigraphic categories was a bit mixed between typical human indicators (P) and natural elements (Si), as was also found in similar context. Nevertheless, such mixing was well diversified by multivariate analyses in the Chotěbuz-Podobora dataset. Therefore, the interpretation was that there is strong and well distinguishable anthropogenic signal on the hillfort connected mainly to P and Mn, and to Cu and Zn. As revealed from the micromorphological results, mainly layers related to Hallstatt period and 9th century occupation are extremely rich of phosphatic pedo-features and presence of bones and burned bones. These features give the soil the strong phosphorus signal. All archaeological layers show the high dependence on oxidation/reduction processes with the development of Fe/Mn nodules, so the increased values of Mn are quite predictable. The geochemistry was also influenced by (potentially) recent deposition by As and Pb. Such pollution was identified previously also in the alluvial plain of nearby river (Faměra et al., 2018). Based on the connection to specific elements and also to areas and sediments of anthropogenic influence, we interpreted these signals as anthropogenic: negative values of PC1 (probably recent), positive values of PC2 (archaeological signal), positive values of PC3 (probably recent), positive values of Comp1 (archaeological signal), negative values of Comp1 (probably recent), positive values of Comp2, negative values of Comp3 (distinguishing between anthropogenic Mn and natural P), positive values of Comp4 (P), negative values of Comp5 (Pb and Sr, whereas positive values represent natural aspect of As). The analyses show usual ways of distinguishing anthropological and natural signals: whereas traditional PCA performed on elemental content showed distinction between main categories of signals (natural vs archaeological vs recent anthropogenic), the PCA on ilr-transformed data (respecting compositional character of geochemical data) focuses on elements with more variability (usually anthropogenic indicators) and therefore distinguishing more the diversified aspects of anthropogenic signals.

6.4. Unraveling AH Structures in Soils and the Impact of Ants on Archaeological Inferences

The macroscopic identification of former AH structures, especially within archaeological contexts, is complex. Subterranean portions of ant nests, intended to be of similar thickness as their above-ground counterparts, often manifest as shallow depressions in the soil. These depressions result from bioturbation or agricultural practices. Detecting ant activity without overt signs involves potential indicators such as macro-remains concentration, chemical signal enhancement, or micromorphological changes. While the archaeobotanical dataset for this study was limited, intriguing observations were made. For instance, *Picea sp*. needles were absent from the core of recent AH ant nests, contrasting with their presence in reference soil samples. Conversely, higher concentrations of other plant debris were noted within the nest's core. After nest collapse and organic matter decay, nutrient retention contributed to elevated phosphorus (P) concentrations. Increased phosphorus (P) and nitrogen (N) levels, coupled with higher total organic carbon (TOC), were linked to organic matter accumulation. Degraded organic matter also correlated with localized increases in mercury (Hg) and lead (Pb). Significantly, soil microstructure emerged as a crucial indicator of ant activity. The presence of typical granular microstructures played a pivotal role in confirming former AH structures at various sites. For instance, microstructures at Le Verger (former AH) mirrored those at Le Theurot de la Roche (recent AH). The *Formica s. str*. group, characterized by regular migratory behavior, is likely to leave cryptic macroscopic evidence of their construction endeavors. Formica ants are known to excavate nests between 0.5 and 2 meters deep into the soil profile, relocating nests and creating satellite nests. A common approach involves quantifying nest number and size per unit area, allowing estimation of ant-driven soil modification over time. Multiple nests on a site suggest prolonged ant-driven soil reworking under stable environmental conditions. In the context of research at La Terrasse (Lisá et al., 2021), aimed at understanding human influence on soil, notable disparities in chemical composition, grain size distribution, and magnetic signals emerged. Micromorphological granule identification throughout the site further indicated the substantial impact of long-term ant activity on soil characteristics. Hence, heightened attention is warranted for potential ant nest presence in archaeological sites. The subtle yet impactful effects of ant activity can significantly influence soil structure, a crucial component of the sedimentary archive essential for comprehending landscape formation processes within an archaeological context.

7. Conclusion

The vast majority of the archaeological record is in one way or another part of the soil and therefore affected by soil processes that rework the remains of past human activities studied by archaeologists. During all our interventions into the subsurface archaeologists constantly observe soils though we rarely see them and record them as such, which may have negative consequences for our understanding of the contexts we observe. The study showed several important and interesting results. One of them is the general observation on problematic of soil record in archaeological contexts. So far there doesn’t exist the exact terminology for soils influenced in past by human action in different intensity and consequences. The differences between terms like cultural layer or Anthrosols or Dark Earth are often used as synonyms, without explanation of detail formation processes. The distribution and interpretation of variable geochemical composition of soil record was one of the main goals of the paper. The soil record detected at the site contained high amount of phosphorus, even higher than usually recorded at abandoned medieval villages.

Currently, the pXRF methodology has been increasingly used in applied geochemistry and successfully provided compositional data in the mining industry and environmental sciences, among others. Its main contribution is providing a rapid and cost-effective alternative to classical laboratory protocols. A well-maintained and calibrated pXRF analyzer provides soil chemistry compositional data that are in good correspondence to other analytical methods. Providing real-time analytic data either directly in the field or in laboratory environment, pXRF is today a strong technique in many disciplines, such as waste management, environmental remediation, geology, mineral extraction, archaeology etc. Providing a high spatial density data in field, site prospection has thus received a substantial enhancement. Having acknowledged the known limits and potential shortcomings of the pXRF analyses, it has become clear that this methodology has become a standard and indispensable part of the toolkit of contemporary research, especially where the soil composition data and its variability provides the critical insight into the classification of sediments and the interpretation of their genesis (e.g., natural vs. artificial origin).

Our findings highlight ants' substantial influence on soil structure and geochemical signals. The geochemical signal from ants can potentially overlap with that of the organic-rich cultural layer. Notably, the ultrafine pedogenic fraction, as measured by χFD%, is higher in the lower section of recent ant nests compared to the reference soil. This observation implies a possible connection between the presence of small granules in the archaeological record and ant activity. The dispersion of these microgranules could contribute to the variability in soil geochemical, magnetic, and physical properties across the La Terrasse site. As a result, we propose that the formation and disappearance of ant structures may trigger significant structural and chemical modifications in archaeological site soils. Therefore, it is imperative to consider this aspect fully when interpreting soil sections. Superparamagnetic fraction quantified by χFD% show the most increased pedogenetic activity in the lower part of the ant heap compare to all examined soils. Ants are able to translocate organic remains like charcoal and macro-remains into the nest and vertically within the nest. By this way they are able to influence the position of the material used for C14 dating.

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"Out beyond ideas of wrongdoing and right doing, there is a field. I'll meet you there. When the soul lies down in that grass, the world is too full to talk about. Ideas, language, even the phrase "each other" doesn't make any sense. The breeze at dawn has secrets to tell you. Don't go back to sleep. You must ask for what you really want. Don't go back to sleep. People are going back and forth across the doorsill where the two worlds touch. The door is round and open. Don't go back to sleep."

Rumi

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8. References

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9. Curriculum vitae, list of publications and other activities

Sahar Poledník Mohammadi

Address: Ovesna 1873, Hostivice 25301
Research links: orcid.org/0000-0001-6556-3187 (ORCID)
linkedin.com/in/sahar-poledn%C3%ADk-645050236/
researchgate.net/profile/Sahar-Polednik-2 (Reseachgate)

Email: mohammadis@fzp.czu.cz
Saharmohammadi46@yahoo.com

Educations

2020- Present	Faculty of Environmental Sciences, Department of Environmental Geoscience, Czech University of Life Sciences Prague -Ph.D. studies -Applied ecology
2015-2017	Department of Soil Science, Tabriz University, Iran -Master studies -Soil science

List of Publications

Sahar Poledník Mohammadi, Jan Horák, Lenka Lisá, Jana Grytz, Hana Grison, Aleš Bajer, Ladislav Šmejda., 2023. Soils as an environmental record of changes between Iron Age and Medieval occupations at Chotěbuz -Podobora hillfort, Geoderma, Volume 429, 2023, 116259, ISSN 0016-7061, https://doi.org/10.1016/j.geoderma.2022.116259.

Lenka Lisá, **Sahar Mohammadi**, Petra Goláňová, Mária Hajnalová, Aleš Bajer, Piotr Moska, Jan Rohovec, Přemysl Král, Jan Kysela, Romana Kočárová., 2022. Detection of occupational surface remnants at a heavily eroded site; case study of archaeological soils from La

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Lenka Lisa, **Sahar Poledník mohammadi**, et al., 2023. The impact of ant bioturbation activities on evolution of archaeological soils-Case of study Celtic oppidum Bibracte (Holocene-revise).

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Teaching activities

- Reviewer of bachelor thesis: Daniel Maršák., 2022. HOLOCENNÍ KLIMATICKÉ OPTIMUM V OBLASTI ÍRÁNU: GEOARCHEOLOGICKÉ A KLIMATOLOGICKÉ STUDIUM VE SPOJITOSTI S LIDSKÝM OSÍDLENÍM. JIHOČESKÁ UNIVERZITA V ČESKÝCH BUDĚJOVICÍCH. FILOZOFICKÁ FAKULTA. ARCHEOLOGICKÝ ÚSTAV.
- Seminar-teaching: Pedology and Micromorphology.,2021. (Assoc. Professor dr. Lenka Lisa). Pilsen.
- Seminar-teaching: Soil Micromorphology.,2020. (Assoc. Professor dr. Lenka Lisa). Pilsen.
- Seminar: The High Medieval croft plužina in the mountainous region of Central Europe: origin and soil development of agricultural terraces from Debrné, Czechia - Poland
- Workshop: Archaeology and Pedology- Spain. 2022.
- Seminar: Iran, Anthropology department- Pilsen (PhDr. Ladislav Šmejda, Ph.D.)
- Workshop: Royal Microscopical Society, 2021. United Kingdom (online).
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