



# The past in dust: current trends and future directions in Pleistocene geoarcheology of European loess

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**ABSTRACT:** Loess is a main archive of Pleistocene landscapes and environments and therefore has an important connection to the preservation and interpretation of Paleolithic sites. In Europe, anthropogenic sites have been found in loess because of past local occupation. At one extreme, sites are well preserved with minimal disturbance often accompanied by embedded proxies to estimate ecological parameters. On the other hand, loess deposits have undergone post-depositional alterations such as weathering, pedogenesis or bioturbation due to changing environmental conditions or other disturbances that obscure anthropogenic sites. We outline the current state of research and connections between Paleolithic archeology and loess research while introducing a series of subsequent regional case studies as part of a special issue. We also make recommendations for future work to incorporate a wider variety of methods to create more robust inferences on hominin and environmental evolution and their connections. © 2021 The Authors *Journal of Quaternary Science* Published by John Wiley & Sons Ltd

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## Introduction

In recent decades, geoarcheology has been shifting from the application of earth science techniques to the archeological record, towards an increased integration of geoscientific methods and concepts to interpret archeological contexts (Pollard, 1999; Rapp and Hill, 2006, p. 22; Goldberg and Macphail, 2009; Fouache, 2013; Canto, 2015; French, 2015; Gilbert, 2016). Whereas sediments were formerly seen as static site repositories, they are now regarded as remnants of past dynamic landscapes and environmental evolution that are intimately connected to their embedded cultural residues and capable of contextualizing but also obscuring behavioral interpretations. This framework has positioned geoarcheology to uniquely inform aspects of prehistory and its connection to the environment that are important for understanding cultural evolutionary trajectories and elaborating the mechanisms that underpin our past and present relationship to global evolution.

The aim of this special issue is to do precisely that through a series of papers exploring the chronostratigraphy, environmental and ecological background and site formation processes of Paleolithic sites embedded in European loess. The articles are organized roughly from north-western to south-eastern Europe, starting with a detailed investigation of Middle Pleistocene loess–paleosol deposits in northern France (Antoine *et al.*, 2021), followed by a study about the impact of katabatic winds on the Neanderthal environment (Lefort *et al.*, 2021), and several studies concentrating on Upper Paleolithic sites (Moine *et al.*, 2021; Molnar *et al.*, 2021; Sümegi *et al.*, 2021; Valde-Nowak and Łanczont, 2021). Finally, we present studies dealing with methodological

investigations and paleoenvironmental focus in several loess–paleosol sequences and one lacustrine record in central and south-eastern Europe (Krauss *et al.*, 2021; Ludwig *et al.*, 2021; Marković *et al.*, 2021a; Zeeden *et al.*, 2021).

Loess is a main sediment archive preserving European Pleistocene artifacts and has therefore long played an important role in Paleolithic archeology. The formal description of loess emerged coeval with the notion of Europe's Pleistocene antiquity and the study of both has evolved, often in tandem, ever since (Marković *et al.*, 2016; Ding *et al.*, 2019). While the recognition of the Paleolithic is commonly attributed to early cave excavations and advances in fluvial terrace stratigraphy (Pettitt and White, 2014; de la Torre, 2016; Chauhan *et al.*, 2017), Paleolithic artifacts were also recognized early in Quaternary loess series in Northern France and Belgium. Loess has therefore had an important historical role in forming concepts and definitions of the Paleolithic (Zeuner, 1956; Sommé and Tuffreau, 1978).

Early research on artifacts embedded in the lower eolian sediments covering the Somme Middle Terrace at Saint-Acheul gave rise to the eponymous Acheulean (Commont, 1916) and the development of the *loess cycle* concept in which alternating layers of loess and paleosols marked climate deterioration and amelioration that were correlated to changes in lithic artifacts over time (Bordes, 1954). Loess research further contributed to the idea that Middle Paleolithic hominins and their tool assemblages were influenced by environmental conditions (Bordes, 1953). In France, for instance, caves and rock shelters in the south and east were thought to have been inhabited by semi-sedentary or sedentary cave-dwellers who intensively retouched Mousterian tools to conserve raw materials. On the north-western loess plateaux, by contrast, mobile Levallois makers discarded unfinished tools when moving on to their next site (Blundell, 2020). While

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such concepts are now regarded as overly simplified, this early practice of linking sedimentary records to hominin ways of life set the stage for Paleolithic research in Europe that continue to be a focus of research today.

While France was a model for many subsequent studies on loess in other loess-rich regions of Europe, Eastern European models of loess were similarly influenced by the Central Asian record. There, the term 'Loessic Paleolithic' has been used to describe Lower Paleolithic sites where lithics are vertically dispersed (1–1.5 m) in pedogenically developed parts of thick loess–paleosol sequences along river terraces (Ranov, 1989, 1995; Schäfer *et al.*, 1998; Davis and Holliday, 2017). This terminology has also been similarly used to describe sites found in the European loess belts of Russia, Ukraine, Germany, Czechia and Poland (Valde-Nowak and Łanczont, 2021).

At a minimum, the history of loess and Paleolithic archeology illustrates that while the two have been inextricably linked, the intimacy of these research strands remains disjointed as no clear consensus has emerged to connect them. In many ways, the absence of true synthetic research between loess research and Paleolithic archeology speaks to the greater uncertainties of how environmental, landscape and hominin evolution are associated. While notable progress has been made, scholars are just beginning to think of new ways of connecting these physical remains of past human culture and environment.

## Background: when the dust settles

Loess is an important terrestrial archive for European Paleolithic archeology stretching back to as early as 2.5–1.8 Ma (Pastre *et al.*, 1996). These records are often (semi-)continuous and encompass the same timeframe as current models of Pleistocene hominin presence. However, loess is often a generic term for sediments formed by multi-genetic processes described by a wide range of unstandardized vocabulary (Sprafke and Obrecht, 2016). Unsurprisingly, the definition of loess and its formation processes are still not settled (Smalley and Obrecht, 2018).

Compared to other prime Pleistocene sedimentary records such as karstic traps and fluvial terraces deposits (Table 1), loess deposits are more locally widespread across Europe, often with greater temporal depth and resolution (Haase *et al.*, 2007; Bertran *et al.*, 2016; Lindner *et al.*, 2017; Lehmkuhl *et al.*, 2021). Where chronological patterns are not entirely clear, these can be potentially refined allowing for broader, landscape-wide interpretations of the archeological record (Zeeden *et al.*, 2018). Indeed, the spatial extent of loess and its effects on preserving human traces is a feature that has

been remarked upon previously. Increased sedimentation amplifies opportunities for capture and preservation of artifacts, and hence the greater chance for sites to enter the Paleolithic record (Roebroeks and Speleers, 2002; Hijma *et al.*, 2012; Antoine *et al.*, 2015).

Outside the mid-latitudes of Europe, loess accumulation is often restricted to periglacial incised valleys, coastal capture points or dolines (Fig. 1; Cremaschi *et al.*, 2015; Scott *et al.*, 2019). However, in regions where loess-mantles are no longer present, eolian sediments are also preserved in isolated areas such as fissures or caves (Kovács *et al.*, 2020). These features can often be important repositories of Paleolithic artifacts (Peresani *et al.*, 2008; Pope *et al.*, 2013; Allsworth-Jones *et al.*, 2018a) and can assist in age and landscape correlations when absolute dating is not feasible (Krajcarz *et al.*, 2016a; Allsworth-Jones *et al.*, 2018b). Where caves and rockshelters are abundant, they also inform interpretations of how hominins modulated their responses to open-air sites (Madeyska, 2002; Delpiano *et al.*, 2019). Figure 1 demonstrates the close spatial relationship of European loess deposits, karst and Paleolithic sites.

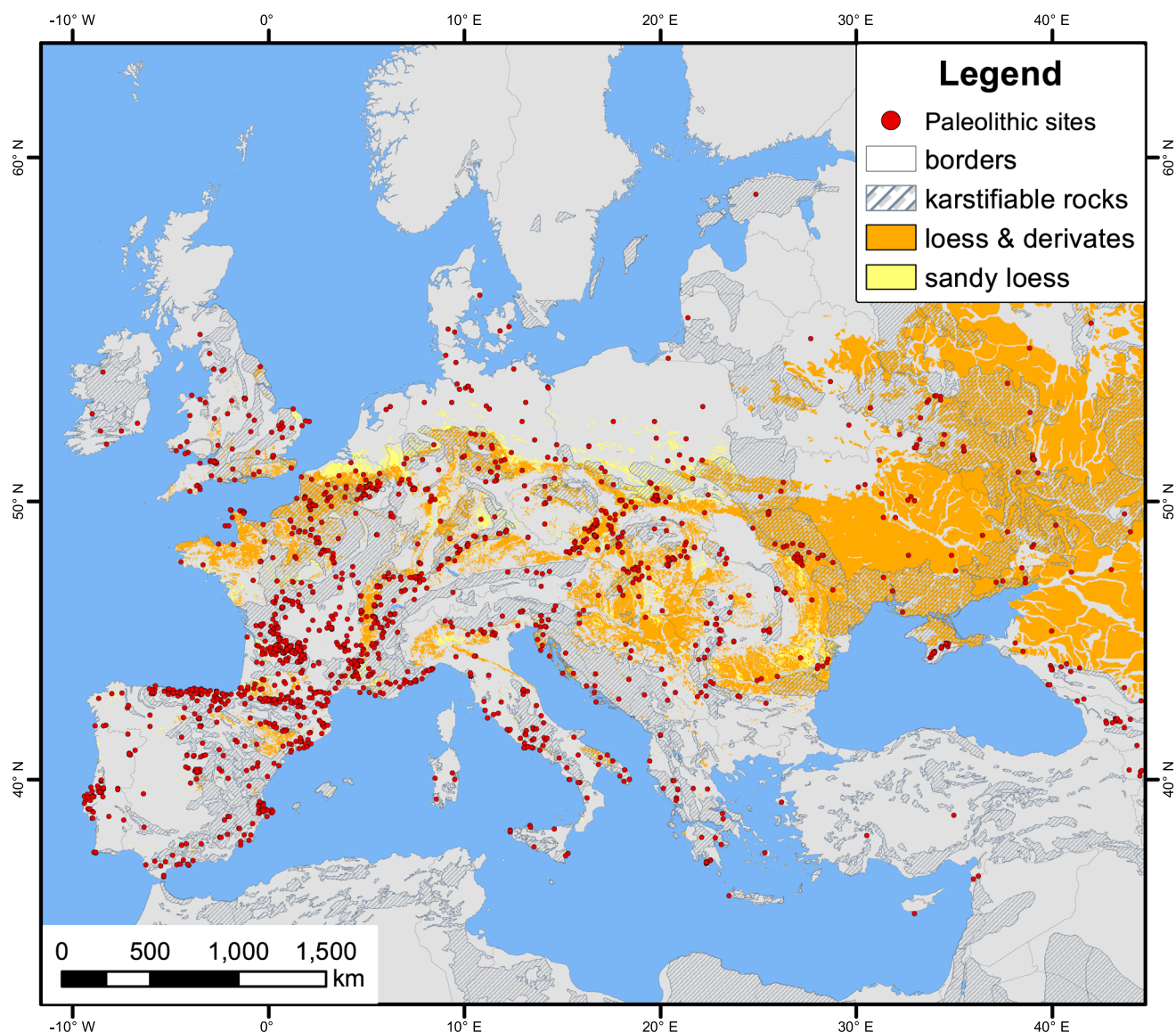
Loess records are unique insofar as, like other widespread terrestrial records, they can address broad-scale spatiotemporal changes (Ashton and Hosfield, 2010; Antoine *et al.*, 2021), but they can also provide windows into brief moments in time. The fluvial record, which preserves many of the Paleolithic artifacts recovered in Europe, is predominantly composed of coarse-grained deposits that obscure the spatial arrangements of sites. By contrast, the low-energy deposition of Late Pleistocene loess-forming dust is known to finely preserve archeological sites with minimal spatial redistribution that can often be refitted to an impressive degree (Roebroeks *et al.*, 1997; Vallin *et al.*, 2001) and are even occasionally suitable for usewear and residue analyses (Sano, 2012; Pawlik and Thissen, 2017; Wilczyński *et al.*, 2020). Loess records are also excellent repositories of faunal prey, fire features, pits, habitation structures and early hominin burials that provide singular insights into local hominin behavioral patterns (Iakovleva and Djindjian, 2005; Händel *et al.*, 2009; Trinkaus and Buzhilova, 2018; Fewlass *et al.*, 2019). To contextualize these sites and document broader ecological evolution, researchers have developed a range of geochronological and proxy analyses for loess.

## Dating methods applied in loess sediments

An array of dating methods are used to determine the timing of loess deposition and the direct ages of artifacts. The most

**Table 1.** A comparison of main Paleolithic archives in Europe

	Loess	Fluvial	Karstic
Distribution	Widespread across mid-latitudes with thicker deposits in the north-west, eastern Central Europe and western Russia (Bertran <i>et al.</i> , 2016)	Widespread, though earlier Pleistocene deposits often absent or altered by the advance of ice sheets in the north (Bridgland <i>et al.</i> , 2015)	Widespread though largely concentrated in uplands and the west and south (Goldscheider <i>et al.</i> , 2020)
Local preservation	Fine, though often colluviated in areas of rugged terrain, on steeper slopes (Bertran <i>et al.</i> , 2016)	Variable, though archeological finds are primarily recovered from coarse-grained gravel deposits (Chauhan <i>et al.</i> , 2017)	Fine, though variable according to cave/rockshelter morphology and hydrological regimes
Common absolute dating techniques	Luminescence, electron spin resonance, radiocarbon (Chu, 2018)	Luminescence, electron spin resonance, cosmogenic nuclides, amino acid racemization	Luminescence, electron spin resonance, radiocarbon, U/Th
Frequently used paleoenvironmental proxies	Rock magnetism, geochemistry, color, grain-size, charcoal, (micro)fauna (Obrecht <i>et al.</i> , 2019)	Pollen, plant macrofossils, charcoal, phytoliths, (micro)fauna (Cordier <i>et al.</i> , 2015)	Pollen, plant macrofossils, charcoal, phytoliths, (micro)fauna (aDNA), stable isotopes



**Figure 1.** Distribution of European loess, loess derivates, sandy loess (using Bertran *et al.*, 2021; Lehmkuhl *et al.*, 2021) and karstifiable bedrock (from Chen *et al.*, 2017). Reliably dated pre-Holocene sites are derived from Vermeersch (2020). [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)].

common are luminescence dating, radiocarbon dating and magnetic stratigraphy, though their use is dictated by the age range under investigation and the availability of suitable material for dating. Due to their eolian origin, loess deposits are widely analyzed by luminescence dating, which determines the age of the accumulation of quartz and feldspar minerals after a bleaching event, usually the last sunlight exposure during eolian transport before deposition (e.g. Böskén *et al.*, 2017; Lomax *et al.*, 2019; Stevens *et al.*, 2020; Stone and Fenn, 2020; D'Amico *et al.*, 2021). Depending on the available grain size, single grain or single aliquot techniques are typically used. For very fine loess deposits that do not contain enough coarse material, single aliquot methods are exclusively applied where a layer of ~1 million grains between 4 and 11  $\mu\text{m}$  is deposited on a single aliquot to be measured: this results in an average dose per aliquot. Coarser grains (>63  $\mu\text{m}$ ) can additionally be measured by the single grain technique, which determines a dose per grain for each of the 100 holes in the aliquot disc. The dose distribution of these data can be analyzed, such as for partial bleaching events (e.g. Reimann *et al.*, 2012). Additional to optically stimulated luminescence (OSL) dating, heated artifacts can also be dated by thermoluminescence methods, thereby providing a direct

age of the heating event (Martini *et al.*, 2001). Note that this age does not reflect the age of sediment deposition and in general post-depositional processes can affect the age distribution. More recently, electron spin resonance (ESR) dating has been applied to Chinese loess deposits (e.g. Richter *et al.*, 2020), which works similar to luminescence dating, but measures the trapped electrons in certain paramagnetic centers by ESR spectrometry (Grün and Stringer, 1991).

While luminescence dating can readily be applied to loess deposits, age uncertainties are usually in the range of 5–10% ( $1\sigma$ ); this is less precise than radiocarbon dating, which is frequently used for younger sediments <45 ka. This dating method is ideally applied to organic remains, such as bones or charcoal (e.g. Moine *et al.*, 2021).  $\text{CaCO}_3$  from mollusk shells and earthworm calcite granules (ECGs) can also be suitable for dating though the tendency of some species to burrow and ingest old carbon may lead to erroneous results, underlining the need for multi-material applications (Bosq *et al.*, 2020). However, organic remains are not always preserved because of the high carbonate leaching potential in loess. When absent, bulk sediment samples can also be radiocarbon dated though often with less accuracy (e.g. Scheidt *et al.*, 2021). While luminescence dating determines the time since last sunlight or

heat exposure, radiocarbon dating determines the time since the demise of the organism whose organic carbon is dated. For longer, particularly older sections, correlative dating via magnetic stratigraphy is often applied (e.g. Zeeden *et al.*, 2009; Scheidt *et al.*, 2021). Here, age control is given by 'wobble-matching' fluctuations in rock- and paleomagnetic parameters to known master curves (Scheidt *et al.*, 2021). These parameters are often the magnetic susceptibility, which is elevated in paleosols, or the direction or paleointensity of the Earth's magnetic field. While it can be widely applied, it is difficult to accurately assess age uncertainty since it depends on the quality of the master curve, the wobble matching method (e.g. Blaauw *et al.*, 2018) and the fact that the magnetic signal can be formed at a later time than loess deposition as magnetic minerals form during pedogenesis (see e.g. Maher, 1998; Ahmed and Maher, 2018). Additionally, tephra (volcanic ashes) and heavy minerals can be used as isochronous marker horizons to correlate non-adjacent profiles and deposits (Lowe, 2011; Davies *et al.*, 2015; Pirson *et al.*, 2018).

Still, dating sediments, artifacts or biological remains is seldom straightforward because discrepancies between various dating techniques often arise (Újvári *et al.*, 2014; Zeeden *et al.*, 2021). Comparisons between radiocarbon dating, luminescence dating and magnetic stratigraphy at a Romanian loess–paleosol sequence show that, at least at this site, radiocarbon dating is only reliable for the last 27–25 ka (Scheidt *et al.*, 2021), potentially related to a low organic carbon content and the probable admixture of younger organic carbon into samples (cf. Song *et al.*, 2015). Other studies investigating the saturation behavior of the quartz luminescence signal show that, at least for older samples, quartz is not a reliable dosimeter (Timar-Gabor *et al.*, 2012; Timar-Gabor and Wintle, 2013; Constantin *et al.*, 2014; Anechitei-Deacu *et al.*, 2018; Avram *et al.*, 2020). A particularly difficult example is presented by Groza *et al.* (2019) for the early Gravettian Krems-Wachtberg site (Austria), where the quartz extracts were heavily contaminated by other minerals, resulting in the rejection of half of the measured aliquots. Despite these challenges, several promising studies using, for instance, Bayesian modeling can help to overcome age inversions and reduce uncertainties (e.g. Schmidt *et al.*, 2021).

### *Inorganic proxy methods in loess*

Because of its eolian genesis, loess can be a reliable marker for past atmospheric circulation to infer paleoclimate patterns using sedimentological, biological, geophysical and geochemical indicators (Rousseau and Hatté, 2021). Its potential for paleoclimatic reconstruction coupled with its widespread nature in the northern hemisphere is the main reason why loess deposits have been intensively investigated. While loess deposits are generally lower in resolution than layered or varved marine and limnic sediments, they provide an opportunity to investigate paleoclimatic and possible paleoanthropogenic archives in a wider spatiotemporal context. Moreover, loess proxy data can be correlated with better resolved records such as ice-cores, facilitating links to Greenland interstadials and past European soil development within loess sequences (Rousseau *et al.*, 2017). Finally, loess records are correlated across the entire Eurasian continent, showing remarkable similarities (Haesaerts and Mestdagh, 2000; Bronger, 2003; Marković *et al.*, 2015, 2018a; Laag *et al.*, 2021), although some caution the use of simple correlations between records that might overlook notable differences in some time intervals (Zeeden *et al.*, 2020), or disregard causality or different delay times between proxies (Vandenberghe, 2012).

Loess records often have abundant environmental proxies embedded within them. When accompanying archaeological materials, these can deliver high-resolution, local, continuous paleoecological reconstructions that provide important context to anthropogenic subsistence. When archaeological materials are not present however, they are often correlated with other regional records that document landscape change and occupation history over time (Romanis *et al.*, 2021) and space (Nerudová *et al.*, 2021). At a larger scale still, loess records have been used to inform diachronic changes in paleodemography and typotechnological trends born out primarily in the lithic record by providing an important record of broad-scale regional and temporal environmental change (Morgan *et al.*, 2011; Schmidt and Zimmermann, 2019) even if analytical units are still precarious (Reynolds, 2020).

Loess grain-sizes can provide information on paleoclimate (Újvári *et al.*, 2016). Loess grain-sizes are usually homogenous and well-sorted but distributions change during or after depositional events such as erosion, transport and soil formation. Variations in these distributions through time (i.e. depth) can infer information about climatic and environmental conditions. More recently, Schulte and Lehmkuhl (2018) presented a method indicative of the degree of chemical weathering in loess–paleosol sequences. However, grain-size is not only analyzed in pure sediment research, but often applied as a component of geoarchaeological investigations (e.g. Chu *et al.*, 2018; Marković *et al.*, 2021b; Malinsky-Buller *et al.*, 2021). For instance, the importance of an in-depth understanding of the loess stratigraphy before any paleoenvironmental proxy interpretation has been emphasized for the Krems-Wachtberg site (Austria; Sprafke *et al.*, 2020) where grain-size analysis allowed a differentiation between eolian sediments and those reworked by slope processes. The study by Händel *et al.* (2021) further illustrates the synergies between archaeology, field observations and granulometry and how they can refine site formation processes.

Inorganic geochemistry is applied to investigate the dust provenance area and the degree of weathering and soil formation. Although there are more suitable methods for provenance studies, such as zircon chronology (e.g. Újvári *et al.*, 2012; Ducea *et al.*, 2018), bulk geochemical analysis holds potential to distinguish different sediment sources and transport pathways (Pötter *et al.*, 2021b). To determine the degree of weathering, several indices are available that rely on the concept of mineral alteration whereby the selective removal of soluble and mobile elements is compared to a relative enrichment of immobile and non-soluble elements (Buggle *et al.*, 2011; Obrecht *et al.*, 2019). This proxy method is frequently used in geoarchaeological studies, mainly to provide the paleoenvironmental context of human occupation (e.g. Degryse and Alexander Bentley, 2017; Böskén *et al.*, 2019, 2018; Chu *et al.*, 2019).

Color measurements of loess or soil samples are also used to estimate paleoenvironmental change. While pure loess sediments are typically light yellow, red and black hues are related to pedological processes or humification (e.g. Sprafke *et al.*, 2020). Spectrophotometric measurements can be performed on sediment samples in the laboratory (Eckmeier *et al.*, 2010; Gocke *et al.*, 2014; Krauß *et al.*, 2016) or digital images can be analyzed to work non-destructively (Zeeden *et al.*, 2017). A further parameter used in loess research is the redness index (Barron and Torrent, 1986). Krauss *et al.* (2021) interpret the color together with further geochemical data as a weathering proxy at the Attenfeld loess–paleosol sequence. Color data can be also analyzed statistically, as, for example, done at the Malá nad Hronom loess–paleosol sequence (Slovak Republic). Here, a hierarchical cluster analysis was

applied to characterize the entire reflectance spectrum and to classify various sediment groups (Szeberényi *et al.*, 2020).

The presented methods work usually best when applied in a multi-proxy approach. There are numerous examples in loess and geoarchaeological studies. For instance, at the Bůhzař site (Czech Republic) geochemical approaches [total organic carbon, X-ray fluorescence (XRF) elemental analyses, X-ray diffraction (XRD) mineralogy,  $^{13}\text{C}$  and  $^{18}\text{O}$  stable isotopes] are combined with grain-size distributions and OSL dating to assess the climatic conditions at the time of formation of the strata (Flašarová *et al.*, 2020). At the Upper Paleolithic site of Temerești (Romania), post-depositional site formation processes were investigated by a multi-proxy approach using geographic information system (GIS), grain-size and geochemical analyses and geochronological methods (Chu *et al.*, 2019). Further early illustrative examples of multi-proxy analysis with geoarchaeological context were undertaken at Maastricht-Belvedere (Van Kolfschoten and Roebroeks, 1985; Vandenbergh *et al.*, 1993).

### Organic proxy methods in loess

Although organic carbon contents are usually low in pure loess deposits, both macro- and micro-vertebrate skeletal remains can be impressively well preserved in loess, such as mollusk shells (Bösken *et al.*, 2018; Moine *et al.*, 2021) or faunal bones that are used to understand the paleoenvironment and behavioral practices (Einwögerer *et al.*, 2006; Montalvo *et al.*, 2008; Marković *et al.*, 2014; Wilczyński *et al.*, 2015). The underlying mechanisms of loess formation or loessification, sometimes regarded a pedogenetic or diagenetic process, is still incompletely understood, though it is suggested to involve trapping of eolian dust or silt, carbonate cementation and further secondary loessification processes such as pedogenesis, re-deposition or compaction (Sprafke and Obrecht, 2016). These can rapidly affect bone diagenesis and, in some cases, erase mammalian skeletal remains completely (Machová *et al.*, 2020).

While other Quaternary paleoecological microfossils such as foraminifera, ostracods, radiolaria, diatoms and pollen are often not preserved in loess (Muhs, 2013), there are exceptions in reworked loess sediments in lacustrine and alluvial settings such as anomalous subaqueous loess facies (Kulesza *et al.*, 2020). The high carbonate content of loess deposits, however, is ideal for the preservation of terrestrial mollusks. Mollusks are sensitive to environmental changes and since modern analog assemblages are widely available, they represent a detailed paleoenvironmental proxy (e.g. Rousseau *et al.*, 2018; Sümeği *et al.*, 2021). These proxy data inform about summer temperatures and moisture conditions (e.g. using the malaco-thermometer method of Sümeği, 1989; Sümeği and Krolopp, 2002) and provide information about habitats, landscape types (dense or open) and vegetation types (boreal/deciduous forest, grassland, tundra, etc.). Many studies deal with the paleoenvironmental reconstruction based on these land snails in loess (e.g. Rousseau, 2001; Sümeği and Krolopp, 2002; Marković *et al.*, 2007; Gerasimenko and Rousseau, 2008; Moine, 2008; Sümeği *et al.*, 2011; Zong *et al.*, 2020) by combining them with sedimentological, magnetic and geochronological data (see Marković *et al.*, 2021a). However, there has been discussion about its interpretation in the Carpathian Basin since some mollusk-based temperature reconstructions do not agree with stable carbon isotope-based ones (Obrecht *et al.*, 2019, 2021; Sümeği *et al.*, 2021). Nevertheless, Ludwig *et al.* (2021) compared Last Glacial Maximum (LGM) temperature reconstructions based on the malacothermometer method with a high-resolution regional climate simulation and found close agreement for the Serbian Vojvodina region. Additionally, they showed different

aridity gradients in the region in comparison to current climate conditions. Finally, some mollusk shells are well suited for radiocarbon dating (Újvári *et al.*, 2017, 2014; Molnár *et al.*, 2021). However, it is crucial to identify those taxa that do not (or only in low amounts) incorporate old carbonates (i.e. dead carbon), which are abundantly available in loess deposits (Újvári *et al.*, 2014).

Another biological proxy investigated in loess–paleosol sequences are ECGs that are common in western and central Europe, but rarer in the arid environments of Asia (Fenn and Prud'homme, 2020). ECGs are composed of rhombohedra calcite crystals produced by a biomineralization processes (Canti, 1998; Gago-Duport *et al.*, 2008; Fenn and Prud'homme, 2020). ECGs are linked to soil temperature and humidity and because they are produced mainly during the spring and autumn, they can be related to paleotemperature (Prud'homme *et al.*, 2016), paleoprecipitation (Prud'homme *et al.*, 2018) and seasonal climate fluctuations (Satchell, 1967; Fenn and Prud'homme, 2020) by their carbon and oxygen isotopic composition. They purportedly reflect conditions in the topsoil (Canti and Pearce, 2003) with limited mixing between different units, making ECGs a powerful paleoproxy that can also be radiocarbon dated (Moine *et al.*, 2017). A detailed and insightful example is given by Moine *et al.* (2021), which presents a first study combining high-resolution malacological data with radiocarbon-dated ECGs at the Upper Paleolithic site of Amiens-Renancourt 1 (Somme, France).

Most biological proxies present in loess–paleosol sequences are composed of calcite or aragonite and therefore can be used to analyze carbon and oxygen isotope compositions.  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  values of carbonate proxies can be indicators of vegetation type, precipitation and temperature (Fenn and Prud'homme, 2020).  $\delta^{13}\text{C}$  is a useful proxy for inferring past photosynthetic pathways (C3 vs. C4 plants) and the degree of physiological water stress (Rousseau *et al.*, 2018; Obrecht *et al.*, 2019). It can further be used for paleoprecipitation reconstruction (Hatté *et al.*, 2001; Hatté and Guiot, 2005; Kohn, 2010). The  $\delta^{18}\text{O}$  values of inorganic calcite are influenced by the temperature during formation and the oxygen isotopic composition of water (Fenn and Prud'homme, 2020). In loess, oxygen isotopes are mainly measured on snails or secondary carbonates.  $\delta^{18}\text{O}$  values of soil carbonates are generally driven by temperature, while  $\delta^{13}\text{C}$  values are used to reconstruct the vegetation and environment during the Quaternary. However, temperature and precipitation can be difficult to quantify and disentangle. A new method holds potential by using clumped isotopes applied to terrestrial carbonates providing soil and air temperature estimates for the summer season (Újvári *et al.*, 2019).  $\delta^{15}\text{N}$  is another stable isotope investigated in loess and is applied to soil biogeochemical cycles. Therefore, it has the potential to provide information on the relationship between precipitation and temperature, but more importantly about the openness or closedness of the N-cycle in the ecosystem (Obrecht *et al.*, 2019). While stable organic carbon and nitrogen isotopes can be used to interpret past vegetation patterns and ecosystem qualities, a careful pretreatment (decalcification method) is important to avoid misinterpretation of the data (Pötter *et al.*, 2021a).

Further micro-organic residues that are investigated in loess–paleosol sequences are n-alkanes and fossil glycerol dialkyl glycerol tetraethers (GDGTs). n-Alkanes are plant leaf wax biomarkers used for the reconstruction of the vegetation history as their signature differs in function based on the different vegetation types. GDGTs are membrane lipids produced by archaea and soil bacteria that can adjust their membrane permeability and fluidity to changing environmental conditions (e.g. pH and temperature), by changing their



**Figure 2.** Photo of the Late Pleistocene loess exposure of Vlaşca in the Lower Danube Basin (Photo by Stephan Pötter, 2018).

molecular composition (Obrecht *et al.*, 2019). Based on modern data, n-alkanes nC27 and nC29 dominate in tree and shrub vegetation, whereas n-alkanes nC31 and nC33 were identified to predominate herbs and grasses (Zech *et al.*, 2011a,b; Schäfer *et al.*, 2016; Fenn and Prud'homme, 2020). After a regional calibration, this proxy is used to reconstruct past vegetation cover (e.g. relative proportion of grasses vs. trees; Bush and McInerney, 2013). However, post-sedimentary overprinting of organic matter in n-alkanes is possible in loess–paleosol sequences and needs to be accounted for (Gocke *et al.*, 2011; Zech *et al.*, 2011b; Fenn and Prud'homme, 2020). GDGTs can be used as a proxy for continental air temperatures and soil pH (Weijers *et al.*, 2007). The ubiquitous occurrence of GDGTs in soils offers the potential to independently reconstruct continental paleotemperature from terrestrial deposits (Jia *et al.*, 2013). However, the use in loess–paleosol sequences is cautioned by Zech *et al.* (2012) who found major disagreements with the available stratigraphic, pedological and geochemical data of three sequences. A new procedure for simultaneous extraction of n-alkanes and alkenones from GDGTs has been proposed by Auderset *et al.* (2020).

## Gathering dust: new directions for Quaternary loess and the Paleolithic

Loess is a prime Pleistocene repository of Paleolithic artifacts that is intimately connected to past European sites and landscapes (see example of loess–paleosol sequence in Fig. 2). Widely distributed, loess has the potential to finely preserve Paleolithic sites, fauna and features in a variety of Pleistocene settings that can often be dated using an assortment of absolute and relative dating techniques. Advances in sedimentology and geochemistry have additionally improved the capacity to identify local and broad-scale spatiotemporal changes to the paleoenvironment that can contextualize how we interpret the archaeological record and inform interpretations of how hominins adapted to and shaped these environments (Badino *et al.*, 2020).

Still, current approaches are challenging as loess records are often discontinuous, lack high-resolution absolute chronology and are too generalized to meaningfully apply to the archaeological record. Continued work is needed to establish direct links between paleoenvironments, site occupations and their contents, particularly where site features are not

preserved. Loess formation processes and pedogenesis are still incompletely understood, complicating our understanding of their association with embedded cultural remains. The uneven spatiotemporal distribution of loess and embedded Paleolithic sites across Europe combined with the resolution of current dating techniques still limits our ability to make meaningful inferences of human behavior across Europe sometimes even at the broadest of scales (i.e. Marine Isotope Stages).

Nevertheless, current scholarship is increasingly demonstrating that detailed, multidisciplinary approaches can reveal regional and local shifts in hominin landscape use that provide new opportunities to understanding past adaptations to environmental change. Part of advancing the future of Paleolithic research in European loess therefore involves advancing the way we apply current geoarchaeological methods and identifying ways in which new and existing methods can contribute to our understanding of past hominin behavior and link them to Paleolithic environments and landscapes. Archeological sites are unique datasets and often require tailored analyses to decode their post-depositional processes and significance.

## Geospatial inventorization

An important part of continued Paleolithic research in loess involves identifying suitable loess areas at a variety of scales. Advances in digital geoarchaeology that take advantage of air- and satellite-based remote sensing (Siart *et al.*, 2018), soil mapping (Bertran *et al.*, 2021) and GIS-based predictive modeling are such approaches (Blundell, 2020) that may contribute to our understanding of marginal zones of loess distribution which have hitherto received archaeological little attention. In areas where loess mantles are thin, advances in shallow ground-based remote sensing techniques such as geomagnetics and ground-penetrating radar are uniquely positioned to identify new sites and map local Pleistocene landscapes (Urban *et al.*, 2019; Barbieri *et al.*, 2021). Such methods are seldom employed in European Pleistocene archaeology, but the properties of loess make such thin exposures ideal for identifying distributions of past hearths, pits, stone and bone arrangements indicative of other site 'furniture'. These have the potential to help map diachronic landscape use and provide invaluable new examples of Pleistocene megasites and habitation structures to examine perceptions of space and place (Iakovleva *et al.*, 2012; Maher and Conkey, 2019; Pryor *et al.*, 2020).

Similarly, further field investigations at the European loess distribution periphery may yield deeper Pleistocene deposits that have otherwise been overlooked and might meaningfully contribute to interpretations of hominin demographics throughout the Paleolithic. Dolines, fissures, greda and other open-air sedimentary traps can provide important information from upland areas that have otherwise been eroded (Scott *et al.*, 2019). Even if such investigations lead to meagre archaeological results, they can still provide important comparative paleoenvironmental proxies and can meaningfully contribute to a more wholistic understanding of past hominin landscape use (Fitzsimmons *et al.*, 2020). Here, understanding regional loess formation mechanisms is key (Assadi-Langroudi, 2019). By understanding the processes by which loess, particularly at the margins, is preserved, we can begin to decode the geomorphological processes underlying archaeological site preservation and recovery and begin to decode how these influence interpretations of artifact distribution patterns and inferences on human habitat predilection; these aspects are already known to be biased (Blundell, 2016; Pope *et al.*, 2016).

## Reconstructing environmental processes by artifact condition and loess properties

As the most enduring part of the Paleolithic record, lithics embedded within loess profiles additionally have the potential to inform the loess interpretations and provide crosschecks against paleoenvironmental reconstructions. This should not be extended to using lithic types as chronological tie-points for loess sequences, which can lead to circular argumentation (Egberts *et al.*, 2020). Rather, by regarding the embedded lithics as artificially inserted clasts within the sedimentological sequence, the suite of lithic taphonomic analyses that have been developed can be employed. Here, refits remain an important part of assessing lithic assemblage integrity in loess that can equally inform interpretations of sedimentary mixing (Villa, 1983; Van Kolfschoten and Roebroeks, 1985). Where available, sedimentary structures, artifact fabrics and size distributions are a principal method to understand the spatial distribution of artifact assemblages that can be used to identify subtle changes to site integrity (Lenoble *et al.*, 2008; McPherron, 2018; Händel *et al.*, 2021). How and when artifacts characteristically imbricate within eolian sediments because of post-depositional changes remains an area for future research (Borrazzo, 2016).

Artifact surface conditions can also contribute to understanding the post-depositional movement of lithic assemblages and help inform interpretations of pedogenesis and loess diagenesis (Vallin *et al.*, 2001). Various geochemical weathering patterns (e.g. patinas) commonly found on flaked stone artifacts may eventually inform their syn- and post-depositional contexts and help to disentangle palimpsests in instances where loess deposition has been thin, deflated or disturbed (Glauberman and Thorson, 2012; Glauberman, 2016). At a microscopic scale, understanding lithic surface polishes may provide ways of deciphering initial modes and direction of loess deposition at discard and the intensity and variety of subaerial exposure to freeze–thaw cycles (Burroni *et al.*, 2002; Chu *et al.*, 2015; Bertran *et al.*, 2017; Michel *et al.*, 2019). Such studies might be best combined with the increasing archeometric improvements in tracewear and residue analysis to not only better understand the various *stigmata* that lithic assemblages in loess characteristically exhibit, but also how these may affect our interpretations of experimentally derived examples of lithic usewear and surficial chemical analysis (Kozowyk *et al.*, 2020; Marreiros *et al.*, 2020).

## Linking loess to hominin social and cultural conditions

Beyond examining how loess studies and Paleolithic archeology can better inform the preservation and context of hominin sites, a main goal of future research is to incorporate wider advances from ecology and paleoanthropology to ascertain deeper questions into hominin evolution. In other words, how is loess connected to other aspects of hominin prehistory in more profound ways beyond its preservation qualities?

One way is through loess's connection to past evolving ecosystems. Throughout the Pleistocene, European loess has constituted a homogeneous, (semi-)contiguous mantle across the landmass characterized by high porosity and cation exchange capacity, leading to fertile, well-drained soils (e.g. Schaetzl and Thompson, 2015). At times, even when continent-wide environmental conditions were suboptimal, these fertile sediments sustained a relatively specific, highly productive steppic flora, establishing distinct biogeographic regions with ample megafauna to support substantial predator

communities including early hominins (Blinnikov *et al.*, 2011; Fitzsimmons *et al.*, 2012; Guthrie, 2013, 1982). Particularly in south-eastern Europe, where climate was reliably milder, loess may have played a role in establishing biodiversity preservation zones, hominin refugia and coalescent communities that may have promoted hominin gene flow and been a catalyst for technological innovation (Marković *et al.*, 2018b, 2021a). Here, the high degree of hominin hybridization and diversity of lithic technocomplexes during the Late Pleistocene may be a partial result (Svensson *et al.*, 2021).

Loess may have impacted technosocial innovation in other ways as well. From at least the Upper Paleolithic, loess has also been used to make ceramic sculptures and may have facilitated increased forms and innovations in artistic expression among early hominins (Farbstein and Davies, 2017). Likewise, research at the Upper Paleolithic site of Sungir (Russia) has suggested that early hominin burials there reflect diverse social behaviors and that loess may have also played a role in the modes of mortuary practices (Trinkaus and Buzhilova, 2018). Further research in these areas may begin to show the complex and intertwined relationships that loess and past human behavior have in more direct ways.

In Eastern Europe, where loess is more ubiquitous and extensive, Paleolithic sites may also show how hominin biological and cultural adaptations are linked to loess landscapes. Internal nasal morphology of early *Homo sapiens* at Sungir and Mladeč (Czechia) demonstrate rapid physiological adaptations to the cold and dry climates indicative of the local loess environments (Stansfield *et al.*, 2021). Similarly, the continuous tradition of Upper Paleolithic mammoth megastructures recovered within the Eastern European loess belt may uniquely illustrate how hominins adapted to loess steppes in the relative absence of caves and rockshelters (Demay *et al.*, 2012; Marquer *et al.*, 2012; Shipman, 2015). One avenue of ascertaining this connection may be in assessing the orientation of Paleolithic sites relative to wind direction (Lefort *et al.*, 2019; Lefort *et al.*, 2021).

Regardless of the direct connection of loess to human evolution and its overlap with other autocorrelated features of climate and landscape, loess and archeology are still commonly studied through a dichotomy of 'meaningful' culture and unmeaning nature (Lyons, 2019). We are just beginning to understand the extent to which lithic assemblages and loess connected beyond just their preservation material. Here a reassessment of loess and archeology's mutual goals is necessary with the aim to look beyond the descriptive analysis and correlation of sedimentary and archeological packages. In this regard, loess is uniquely suited to address larger-scale anthropological issues because of its ubiquity across the European landscape and its preservation of Paleolithic artifacts and features throughout the Pleistocene.

## Cooperation and preservation

To date, transcontinental approaches to loess geoarcheology remain largely isolated, at least from a European perspective. While Europe has tended to dominate loess Paleolithic research, increasing scholarship from Asia is rapidly developing new methods and techniques of analysis to meet the challenges of exceptionally long sequences (Krajcarz *et al.*, 2016b; Nian *et al.*, 2016; Zhang *et al.*, 2017; Zhu *et al.*, 2018; Zhao *et al.*, 2021). Likewise, in the Americas, Late Quaternary sites show complex responses of humans and fauna to paleoenvironmental change that can provide important cross-checks to human–environmental interactions derived in Europe (Graf and Goebel, 2017; Powers *et al.*, 2017; Lanoë *et al.*, 2020).

Finally, an area of intersecting interest between geosciences and the Paleolithic archeology must surely be the management and protection of finite loess archives (Vasiljević *et al.*, 2011; Vujičić *et al.*, 2018). Anthropogenic impact, including mining, agriculture and development, increasingly encroach on Europe's loess deposits and key Paleolithic loess sequences have already been erased, making the protection of their landscapes and archeological sites all the more urgent (Nykamp *et al.*, 2017; Antoine, 2019; Bogucki *et al.*, 2020). Geoconservationists, archeologists and earth scientists alike have largely advocated for the establishment of protected areas in the forms of geoparks fueled by the active promotion of sustainable geotourism (Vasiljević *et al.*, 2014; Jary *et al.*, 2018). However, national structures vary across European borders and are commonly split between cultural heritage and environmental protection organizations, leading to disparate methods of identification, classification and preservation regimes. A main goal for geoheritage conservation of loess landscapes is therefore the stronger implementation of international initiatives and policies (Gordon, 2018).

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**Abbreviations.** ECGs, earthworm calcite granules; ESR, electron spin resonance; GDGTs, glycerol dialkyl glycerol tetraethers; OSL, optically stimulated luminescence; XRD, X-ray diffraction; XRF, X-ray fluorescence.

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