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The effect of formation processes on Palaeolithic settlement patterns: insights from south Kazakhstan and the Swabian Jura, southern Germany

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The effect of formation processes on Palaeolithic settlement patterns: insights from south Kazakhstan and the Swabian Jura, southern Germany

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Abstract

Understanding the factors that control the distribution of Palaeolithic sites comprises a fundamental objective of archaeological science. Geoarchaeological approaches focusing on site formation processes have been widely applied to demonstrate the factors that influence the formation and preservation of Palaeolithic sites over time. However, available knowledge is heavily skewed towards extensively researched parts of the world and focuses primarily on the site-specific analyses of landmark Palaeolithic sites. In this context, no previous study used a systematic geoarchaeological approach to investigate the impact of formation processes on a regional level in Central Asia, despite the critical role of Central Asia in hominin evolution and dispersals. Furthermore, as the formation history of low-density archaeological sites remains unaddressed, the role of low-density sites in hominin hunter-gatherer settlement patterns remains elusive, even for regions with a rich Palaeolithic record. On this basis, this PhD thesis performed a multi-scalar approach to the analysis of the interplay between formation processes and settlement patterns, by investigating site distribution on a regional scale in Kazakhstan, Central Asia, and a local scale in the Swabian Jura, Germany, Europe.

Paper I, *“In search of a Palaeolithic Silk Road in Kazakhstan*”, provides a geoarchaeological framework for contextualizing a field survey in the Inner Asian Mountain Corridor (IAMC) of Kazakhstan. The field survey explores the distribution of Palaeolithic sites in a crucial region for Late Pleistocene hominin evolution, testing the fundamental assumptions that govern predictive models of hominin dispersals and behavior in Central Asia. The results revealed that three geomorphic settings, karst, loess, and spring deposits, are the most promising for the formation and preservation of archaeological sites. A detailed discussion explores the systematic biases that influence data collection and interpretation, according to the type of geomorphic context in which the sites are recovered.

In the framework of this systematic geoarchaeological analysis, a primary aim was to investigate the formation processes that influence the formation and preservation of Pleistocene deposits in the most promising geomorphic settings in Kazakhstan, the caves and rockshelters of the Qaratau mountains (Paper II). Paper II, “*The effect of*

formation processes on the frequency of Palaeolithic cave sites in Semi-Arid Zones: Insights from Kazakhstan", combines site-specific data, extracted from the micromorphological analysis of selected caves, and landscape data, extracted from survey observations, to not only interpret but also assess the completeness of the known regional archaeological record. In this way, it sets a novel basis for investigating the formation and preservation of cave deposits in Kazakhstan, with broader implications for the distribution of Palaeolithic cave sites in Central Asia. The results demonstrated that cave formation processes are tied to regional geomorphic and climatic factors, with implications for caves in similar semi-arid settings. Pleistocene deposits are scarce, while aeolian loess-like cave sediments and reworking processes of varying intensity dominate the depositional sequences. Furthermore, hillslope erosion and loess cover impact the long-term preservation of caves in the landscape.

Given the regional scarcity of Pleistocene archaeology in the caves of Kazakhstan, emphasis was given in exploring the formation processes of low-density cave sites and their role in settlement patterns in a more local scale (Paper III). Paper III, "*Low density occupation sites from the Swabian Jura: Implications for site formation processes and settlement patterns*", applies a site-specific approach based on micromorphological analysis, to explore the formation history of selected low-density and anthropogenically sterile cave sites located in the Swabian Jura, Germany, one of Europe's richest regions in terms of Late Pleistocene Palaeolithic assemblages. The results showed that low-density cave sites are dominated by phosphatic features associated with carnivores, demonstrating the use of cave spaces by both predators and hominins. Most importantly, the absence of dense archaeological horizons is not attributed to intense geogenic processes, but rather to hominin intentionality. In this regard, the low-density cave sites reflect sporadic hominin use, most probably associated with specific mobility strategies.

Overall, this PhD thesis identified a clear association between formation processes and the distribution of archaeological sites based on both site-specific and landscape-specific analyses. The regional scale geoarchaeological analysis in Kazakhstan demonstrated that in-built biases characterize the archaeological record in different geomorphic contexts, while geogenic processes triggered by the semi-arid environment may explain the removal of caves from the landscape leading to a low-density distribution of archaeological cave sites. At the same time, the local scale geoarchaeological analysis in the Swabian Jura demonstrated that hominin intentionality and not geogenic processes control the formation of a sporadic low-density archaeological cave record. By understanding the processes that shape the distribution of archaeological sites or the formation of low-density sequences over a given area, we are able to assess the completeness of the archaeological record and construct more accurate interpretations regarding hominin dispersals and settlement patterns.

Zusammenfassung

Das Verständnis der Faktoren, die Verbreitung paläolithischer Stätten steuern, ist ein grundlegendes Ziel der archäologischen Wissenschaft. Geoarchäologische Ansätze, die sich auf die Entstehungsprozesse von Fundstellen konzentrieren, sind weithin angewandt worden, um die Faktoren aufzuzeigen, die die Entstehung und Erhaltung paläolithischer Fundstellen im Laufe der Zeit beeinflussen. Das verfügbare Wissen ist jedoch stark auf die gut erforschten Teile der Welt ausgerichtet und konzentriert sich in erster Linie auf die ortsspezifischen Analysen der wichtigsten paläolithischen Fundstätten. In diesem Zusammenhang wurde in keiner früheren Studie ein systematischer geoarchäologischer Ansatz verwendet, um die Auswirkungen von Formationsprozessen auf regionaler Ebene in Zentralasien zu untersuchen, obwohl Zentralasien eine entscheidende Rolle bei der Evolution und Ausbreitung von Hominինen spielt. Da die Entstehungsgeschichte von archäologischen Stätten mit geringer Dichte nach wie vor nicht erforscht ist, bleibt die Rolle von Stätten mit geringer Dichte in den Siedlungsmustern der Jäger und Sammler von Homininen selbst für Regionen mit einer reichen paläolithischen Überlieferung unklar. Auf dieser Grundlage wurde in dieser Doktorarbeit ein multiskalarer Ansatz zur Analyse des Zusammenspiels zwischen Entstehungsprozessen und Siedlungsmustern verfolgt, indem die Verteilung von Fundstellen auf regionaler Ebene in Kasachstan, Zentralasien, und auf lokaler Ebene auf der Schwäbischen Alb, Deutschland, Europa, untersucht wurde.

Paper I, "Auf der Suche nach einer paläolithischen Seidenstraße in Kasachstan", liefert einen geoarchäologischen Rahmen für die Kontextualisierung einer Feldstudie im Inner Asian Mountain Corridor (IAMC) von Kasachstan. Die Feldstudie untersucht die Verteilung der paläolithischen Fundstellen in einer für die Entwicklung der Homininen im späten Pleistozän entscheidenden Region und testet die grundlegenden Annahmen, die den Vorhersagemodellen für die Ausbreitung und das Verhalten der Homininen in Zentralasien zugrunde liegen. Die Ergebnisse zeigen, dass drei geomorphologische Gegebenheiten - Karst, Löss und Quellablagerungen - am vielversprechendsten für die Entstehung und Erhaltung archäologischer Fundstellen sind. In einer ausführlichen Diskussion werden die systematischen Verzerrungen erörtert, die die Datenerfassung und -interpretation je nach Art des

geomorphologischen Kontextes, in dem die Fundstellen entdeckt wurden, beeinflussen.

Im Rahmen dieser systematischen geoarchäologischen Analyse war es ein vorrangiges Ziel, die Entstehungsprozesse zu untersuchen, die die Bildung und Erhaltung pleistozäner Ablagerungen in den vielversprechendsten geomorphologischen Umgebungen Kasachstans, den Höhlen und Felssilos des Qaratau-Gebirges, beeinflussen (Beitrag II). Beitrag II, "Der Einfluss von Entstehungsprozessen auf die Häufigkeit paläolithischer Höhlenfunde in semiariden Zonen: Insights from Kazakhstan" kombiniert ortsspezifische Daten, die aus der mikromorphologischen Analyse ausgewählter Höhlen gewonnen wurden, mit Landschaftsdaten, die aus Vermessungsbeobachtungen gewonnen wurden, um die Vollständigkeit der bekannten regionalen archäologischen Aufzeichnungen nicht nur zu interpretieren, sondern auch zu bewerten. Auf diese Weise wird eine neue Grundlage für die Untersuchung der Entstehung und Erhaltung von Höhlenablagerungen in Kasachstan geschaffen, die sich auch auf die Verbreitung paläolithischer Höhlenstätten in Zentralasien auswirkt. Die Ergebnisse zeigen, dass Höhlenbildungsprozesse an regionale geomorphologische und klimatische Faktoren gebunden sind, was wiederum Auswirkungen auf Höhlen in ähnlichen semiariden Gebieten hat. Ablagerungen aus dem Pleistozän sind kaum vorhanden, während äolische, lössartige Höhlensedimente und Umarbeitungsprozesse unterschiedlicher Intensität die Ablagerungssequenzen dominieren. Darüber hinaus beeinflussen Hangerosion und Lößbedeckung die langfristige Erhaltung von Höhlen in der Landschaft.

In Anbetracht der regionalen Seltenheit pleistozäner Archäologie in den Höhlen Kasachstans wurde der Schwerpunkt auf die Erforschung der Entstehungsprozesse von Höhlenstandorten geringer Dichte und ihrer Rolle in den Siedlungsmustern auf lokaler Ebene gelegt (Beitrag III). Paper III, "Low density occupation sites from the Swabian Jura: Implications for site formation processes and settlement patterns", wendet einen ortsspezifischen Ansatz an, der auf mikromorphologischen Analysen basiert, um die Entstehungsgeschichte ausgewählter, anthropogen steriler Höhlenfundstellen auf der Schwäbischen Alb, Deutschland, zu untersuchen, einer der reichsten Regionen Europas in Bezug auf spätpleistozäne paläolithische

Assemblagen. Die Ergebnisse zeigen, dass Höhlen mit geringer Dichte von phosphatischen Merkmalen dominiert werden, die mit Fleischfressern in Verbindung gebracht werden, was die Nutzung von Höhlenräumen sowohl durch Raubtiere als auch durch Homininen belegt. Besonders wichtig ist, dass das Fehlen dichter archäologischer Horizonte nicht auf intensive geogene Prozesse zurückzuführen ist, sondern auf die Absicht der Homininen. In dieser Hinsicht spiegeln die Höhlen mit geringer Dichte eine sporadische Nutzung durch Homininen wider, die höchstwahrscheinlich mit spezifischen Mobilitätsstrategien verbunden war.

Insgesamt konnte im Rahmen dieser Doktorarbeit ein klarer Zusammenhang zwischen Entstehungsprozessen und der Verteilung archäologischer Fundstellen festgestellt werden, der sowohl auf standortspezifischen als auch auf landschaftsspezifischen Analysen beruht. Die geoarchäologische Analyse auf regionaler Ebene in Kasachstan hat gezeigt, dass die archäologische Überlieferung in verschiedenen geomorphologischen Kontexten durch eingebaute Verzerrungen gekennzeichnet ist, während geogene Prozesse, die durch die halbtrockene Umgebung ausgelöst werden, die Entfernung von Höhlen aus der Landschaft erklären können, was zu einer geringen Dichte archäologischer Höhlenstandorte führt. Gleichzeitig hat die geoarchäologische Analyse auf der Schwäbischen Alb gezeigt, dass die Entstehung sporadischer archäologischer Höhlenfunde mit geringer Dichte nicht durch geogene Prozesse, sondern durch die Intention des Menschen gesteuert wird. Wenn wir die Prozesse verstehen, die die Verteilung archäologischer Stätten oder die Bildung von Sequenzen mit geringer Dichte in einem bestimmten Gebiet bestimmen, können wir die Vollständigkeit der archäologischen Aufzeichnungen beurteilen und genauere Interpretationen bezüglich der Ausbreitung und der Siedlungsmuster von Homininen vornehmen.

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List of publications for cumulative dissertation

Paper I

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Paper II

Varis, A., Miller, C., Cuthbertson, P., Namen, A., Taimagambetov, Z., & Iovita, R. (2022). The Effect of Formation Processes on The Frequency of Palaeolithic Cave Sites in Semi-Arid Zones: Insights From Kazakhstan. *Geoarchaeology*. https://doi.org/10.1002/gea.21909

Paper III

Varis, A., Miller, C. E., Toniato, G., Janas, A., & Conard, N. J. (2022). Using formation processes to explore low-density sites and settlement patterns: A case study from Swabian Jura. *Journal of Paleolithic Archaeology*. (submitted)

Personal contribution

Publication 1: I was the second author, as well as the person responsible for writing the geoarchaeological part of the manuscript together with the corresponding author, Radu Iovita. As the team's principal geoarchaeologist, I recorded the geoarchaeological field data presented in the paper together with Radu Iovita.

Publication 2: I was the first and corresponding author, and lead author of writing the manuscript. The coauthors helped to conduct the field survey and excavation of the studied caves (Patrick Cuthbertson, Abay Namen, Zhaken Taimagambetov, Radu Iovita), assisted in interpreting the micromorphological thin sections (Christopher E. Miller), helped with figures (Patrick Cuthbertson), provided editorial input (Patrick Cuthbertson, Christopher E. Miller, Radu Iovita) and oversaw the study as a supervisor (Christopher E. Miller and Radu Iovita).

Publication 3: I was the first and corresponding author, as well as the person along with Christopher E. Miller responsible for conceiving the study design and lead author of writing the manuscript. The coauthors helped with figures (Alexander Janas), provided access to the studied material (Christopher E. Miller, Nicholas J. Conard) assisted in interpreting the micromorphological thin sections (Christopher E. Miller), helped in writing the manuscript (Christopher E. Miller and Giulia Toniato), provided editorial input (Nicholas J. Conard) and oversaw the study as a supervisor (Christopher E. Miller).

1. Introduction – Background of the research

1.1. Addressing biases in settlement pattern studies

The analysis of archaeological settlement patterns seeks to explore human behavioral change based on the distribution of the material traces of past human presence across space (Kowalewski, 2008; Feinman, 2015). Artifacts and other archaeological features (such as hearths, storage pits, structures, etc.) constitute the physical manifestations of cultural behavior that, when clustered, form archaeological sites (e.g., Spaulding, 1960; Binford, 1964). Understanding the factors that influence the formation and spatial distribution of archaeological sites is a fundamental research objective in Palaeolithic archaeology, addressing a plethora of questions regarding site use and settlement dynamics. However, the information obtained from archaeological sites can be biased at least in two ways: first, by hominin choices regarding site use and site selection, and second, by the natural processes that influence the preservation and visibility of the archaeological record.

Regarding site use and site selection, Wobst (1983, p. 39) notes that "*human behavior is not uniformly distributed*. It is bound to be strongly clustered, counterposing areas of extreme density with extremes of low density, minimal clustering and maximal dispersion. Yet, the low intensity tails of this distribution are infinite rather than nearly bounded, and peaks are not separated from each other by a vacuum, but by *a continuum of behavioral space* […] The same is true of […] artifacts, as archaeologically most graspable points of behavior - through time, their distribution should acquire an infinite tail. […] *An archaeological distribution is best visualized as a blanket that covers the given area*."

In this framework, various models addressing hunter-gatherer settlement patterns and mobility strategies, have been applied in Palaeolithic contexts to explain the spatial variability that characterizes archaeological distributions and infer hominin behavior (Binford, 1980; Conkey, 1980; Fitzhugh & Habu, 2002; Conard, 2001, 2004; Meignen et al., 2006; Conard & Delagnes, 2010, 2015 among others). Binford's (1979, 1980) and Kelly's (1983) ethnoarchaeological studies distinguishing between logistical and residential mobility have been the most influential (Galanidou, 1998; Picin & Cascalheira, 2020; Speth, 2022). Specifically, according to Binford's (1980) “forager-collector” model, two kinds of sites dominate most hunter-gatherer settlement systems: the residential camps and the task-specific sites. Residential camps have a long-term or seasonal occupation with infrastructural features (e.g., hearths) being the center of social activities, while task-specific locations have an ephemeral use, occupied only for the amount of time necessary to perform the task at hand (e.g., hunting). This “forager-collector” model (Binford, 1980) has received many criticisms including: the limitations of ethnography in reconstructing past hunter-gatherer behavior (Wobst, 1978), the deterministic system that underlies Binford’s middle-range theory and model (Bettinger, 1987; Speth, 2022), the influence of non-utilitarian variables that may trigger mobility (Whallon, 2006), or the lack of mechanisms that explain long-term system changes (Grove, 2009).

Despite the above theoretical concerns and the typological generalizations that govern Binford’s “forager-collector” model, I consider the mobility spectrum introduced by Binford (1979, 1980) as a useful starting point for disentangling archaeological variability in Palaeolithic contexts. The reasoning behind this approach is that hunter-gatherer mobility reflects archaeological visibility based on the concept of occupation intensity; i.e., the length and frequency of occupation or the size of the hunter-gatherer group (Yellen, 1977; Munro, 2004). Higher residential mobility is associated with intense occupation leading to high refuse density over individual sites, while logistical mobility and ephemeral occupation result in a low-density record, with discard concentrated over the landscape rather than in recognizable “sites” (Yellen, 1977; Binford, 1979; Foley, 1981).

Archaeologists have relied heavily on the concept of occupation intensity to explore settlement patterns by using artifact density as an index of population size and occupation span at a site and landscape level (Treganza & Cook, 1948; O’Connor & Veth, 1993; Varien & Mills, 1997 for a review; Balme, 2014; Clark, 2017; Belardi et al., 2021; Haaland et al., 2021). On the site level, find density values have been used to characterize Palaeolithic sites as high density or low-density occupation contexts, with the distribution of artifacts and features providing implications for site structure and population dynamics. On the landscape level, most studies employ a behavioral ecology approach to explore the interplay between hominin site selection and find density values. According to this approach, Palaeolithic sites are not located randomly on the landscape, but are influenced by topographic attributes, such as altitude and aspect, or geomorphological attributes, such as proximity to water sources (G. N. Bailey & Davidson, 1983; Turrero et al., 2013; Henry et al., 2017; Mas et al., 2018; among others). Computational models that predict possible pathways of hominin dispersals constitute the pinnacle of this ecological narrative, aiming to outline a fundamental framework for understanding human evolution (Nikitas & Nikita, 2005; Beeton et al., 2014; Benito et al., 2017; Beyin et al., 2019; among others).

However, ground-proofing the computational models built from find density data remains a challenge, since the formation and preservation of archaeological sites is also influenced by natural processes related to the geomorphic context where the sites are found (Blum et al., 1992; Clevis et al., 2006; Tryon, 2010; Martínez & Martínez, 2011; Iovita et al., 2020; Varis et al., 2022 among others). On the site level, the usefulness of find density values may be compromised by additional biases, such as the rate of geogenic deposition and the formation of activity palimpsests (Jerardino, 1995; Bailey, 2007), spatial heterogeneity of activities (Domínguez-Rodrigo & Cobo-Sánchez, 2017), technological changes (Hiscock, 1981) and various methodological factors including sampling strategy (Binford, 1964; Sánchez-Romero et al., 2021).

Geoarchaeological studies that investigate diachronic changes in archaeological sites and the formation of depositional contexts provide a complementary approach to distributional and ecological studies. However, even within the realm of geoarchaeology, there is a fundamental research gap regarding the formation processes of specific geomorphic contexts and sites with low find density. The following sections provide a more detailed background to the geoarchaeological approach of formation processes and address the research gaps and questions explored in this thesis.

1.2. The geoarchaeological approach of formation processes as a tool for investigating settlement patterns

In my thesis, I used the theoretical concepts of formation-processes and micro-context to explore settlement patterns. Here, I provide a methodological overview of those approaches in the realm of geoarchaeology, while I also outline research advancements and gaps regarding their use in Palaeolithic contexts.

1.2.1. An outline of formation processes and micro-context in geoarchaeology

The use of geoarchaeological approaches has been a turning point for investigating the processes that shape archaeological sites. Geoarchaeology, which is broadly defined as any method that employs geoscience techniques and concepts to archaeological questions (Rapp & Hill, 2006, p. 2), changed the focus of analysis from the typology and spatial distribution of artifacts to the archaeological deposit (Goldberg & Macphail, 2006). The archaeological deposit is a three-dimensional aggregate of sedimentary particles that has accumulated under specific processes (Stein, 1987). Geoarchaeology attempts to explore the processes that lead to the formation of deposits by investigating the contextual relationships between the various sedimentary components (see also Karkanas & Goldberg, 2018b).

In this regard, the theoretical basis for investigating the processes that form archaeological sites and deposits has been introduced by Schiffer (1972, 1983, 1987) under the concept of “site-formation processes”. Schiffer (1972), argues that archaeological assemblages are not the direct result of behavioral patterns, as envisaged by previous middle-range theories, but constitute an aggregate of materials transformed by depositional and post-depositional processes. In Schiffer’s approach, both cultural and natural processes are responsible for the formation of archaeological deposits. Cultural processes are associated with the various behavioral choices that govern the procurement, production, use and discard of artifacts, while natural processes control the patterning and taphonomy of artifacts.

Building upon this formation theory, geoarchaeological approaches have investigated the interplay between cultural and natural formation processes, demonstrating the uniqueness of archaeological deposits in contrast to the exclusively geogenic sediments (e.g., Courty, 2001; Goldberg & Sherwood, 2006; Angelucci et al., 2009; Arroyo-Kalin, 2010; Goldberg & Aldeias, 2018). In this regard, even though archaeological deposits are influenced by a variety of geogenic processes, they are mainly formed by the residues of individual daily events and practices (Courty et al., 1989, p. 4). The aggregation of these residues forms heterogeneous layers of small thickness that can only be addressed by focusing on their micro-contextual relations (Goldberg & Macphail, 2006). Therefore, micromorphology is the ideal geological technique for addressing contextual questions of site-formation processes, since it uses the polarizing microscope to study thin sections of undisturbed and oriented sediments (Courty et al., 1989; Macphail, 2014; Nicosia & Stoops, 2017). Some of the most common research objectives include the type and origin of materials that form a deposit, as well as the depositional and post-depositional change of different particles, highlighting the influence of sedimentary, pedogenic and anthropogenic processes in the formation of archaeological sites (Courty, 1992). Nevertheless, making inferences about past human activities from sediments is rather challenging, given the heterogeneity of archaeological deposits and the difficulty in distinguishing depositional attributes from specific formation processes (Walkington, 2010). Current geoarchaeological research is actively investigating this property-process relationship, effectively demonstrating that the interplay between natural and cultural formation processes produces deposits with distinct diagnostic characteristics (Shahack-Gross, 2017).

1.2.2. The concept of formation processes and its application in Palaeolithic sites: research biases and prospects

In the case of hunter-gatherer Paleolithic contexts, the geoarchaeological study of formation processes using micro-contextual techniques and micromorphology, has provided novel insights into the composition of the Palaeolithic record. By targeting individual Palaeolithic sites, the concept of “site-formation processes” is often used to identify and interpret the natural and anthropogenic factors that influence the diachronic evolution of archaeological sequences (Goldberg & Macphail, 2006; Karkanas & Goldberg, 2018a) . Therefore, pivotal work in various Palaeolithic sites has demonstrated that formation processes affect greatly the depositional context of archaeological remains, the spatial relationship between different assemblages and the overall integrity of the archaeological record (Goldberg et al., 2001; Mallol et al., 2009a; Miller et al., 2013).

In this context, the reconstruction of past activities through the analysis of anthropogenic features and occupation deposits, which are formed by the accumulation of microscopic human activity debris (Shahack-Gross, 2017, p. 37), has received much attention. Combustion features constitute one the best-studied examples of anthropogenic deposits in Palaeolithic sites, providing unique information regarding technological choices and use of space (Karkanas et al., 2007; Goldberg et al., 2009; Berna et al., 2012; Mentzer, 2014). Except from combustion features, micromorphology can also demonstrate other activities related to use of space, such as bedding, sweeping and trampling, (Schiegl et al., 2003; Goldberg et al., 2009; Wadley et al., 2011; Miller et al., 2013). Geoarchaeological analyses have also assessed the completeness of the archaeological record, by investigating the taphonomy of the anthropogenic materials found in Pleistocene sediments. In this regard, geoarchaeologists use the concept of diagenesis, i.e., the physical or chemical post-depositional alteration of materials (Karkanas et al., 2000), to explore the preservation potential of materials in different contexts including ash (Schiegl et al., 1996; Canti & Brochier, 2017), plant (Cabanes et al., 2011), bone (Weiner et al., 1993; Mallol et al., 2010) and coprolites (Goldberg & Nathan, 1975; Brönnimann, Pümpin, et al., 2017). By controlling what constitutes an anthropogenic deposit and its preservation probability through time, geoarchaeological analysis can also target questions of occupation intensity (Wadley et al., 2011; Miller, 2015; Leierer et al., 2019; Haaland et al., 2021),

Despite these advancements, the effect of formation processes in settlement dynamics is not always addressed. Specifically, even though geoarchaeological research has focused heavily on prominent Palaeolithic sites with rich occupation deposits, sites with more ephemeral occupation and a sparser archaeological record have not been investigated thoroughly. From a theoretical perspective, this research bias favors sites with a probable long-term residential use, based on the presence of multi-layered and dense archaeological levels, over sites with a probable short-term logistical use. This research bias skews considerably the interpretative capabilities of Palaeolithic settlement dynamics, if we consider that hunter-gatherer settlement systems integrate sites with different uses and varying occupation intensity (see section 1.1). Furthermore, the focus on understanding the formation processes of prominent sites extends to regions with a high density of archaeological sites over a given area. Regions like South Africa, Central Europe or the Levant are well-researched, while others like Central Asia remain understudied despite their importance in hominin evolution and dispersals (Fitzsimmons et al., 2017).

Except for the above theoretical remarks, the investigation of archaeologically poor sites and regions is also fruitful from the perspective of archaeological practice. Sites and regions with limited hominin occupation may provide a diverse dataset that is notably useful for exploring hominin behavior and preservation bias over a given area. First, sites with ephemeral occupation could bring valuable insights into cultural choices, as they might preserve single occupation events, rather than palimpsests of activities, where multiple activities produce a noisy record (Straus & González Morales, 2021). Second, sites with limited archaeological potential constitute a geogenic archive of the processes that might preserve or remove the remains of human occupation at the site or landscape level (see also Karkanas et al., 2021).

1.3. A multi-scalar approach to the effect of formation processes in settlement patterns

Given the research biases and prospects outlined in section 1.2.2, this thesis explores the effect of formation processes on the reconstruction of settlement patterns. Specifically, it targets Palaeolithic contexts with low find-density that are found in different geomorphic and archaeological contexts, employing a multi-scalar approach developed in two research projects. *Project 1* has a regional emphasis addressing formation processes in Kazakhstan, Central Asia, an understudied but crucial region for hominin evolution. *Project 2* investigates sites with a limited to zero anthropogenic signal in a more local scale, focusing on the settlement patterns of the Swabian Jura, Germany, a landmark region for Palaeolithic archaeology in Europe. A research background on Kazakhstan and the Swabian Jura is provided below.

1.3.1. The necessity of understanding formation processes in Late Pleistocene Central Asia and Kazakhstan

The Inner Asian Mountain Corridor (IAMC; Frachetti, 2012) constitutes a 2500 km-long chain of mountain foothills (piedmonts) flanked by lowland deserts (e.g., Qyzylqum, Qaraqum, Moyunqum,Tauqum, Saryyesik-Atyrau) and high mountains (the Pamir, Alay, Dzungar, and Altai among others), extending from Afghanistan to southern Siberia (Fig. 1). The majority of stratified Palaeolithic sites in Central Asia are located in this piedmont zone, which appears to have served as an ecological niche for hominins and animals alike based on ecological and dispersal models (Beeton et al., 2014; Glantz et al., 2018; Zwyns et al., 2019; Li et al., 2019; Iovita et al., 2020). A ‘northern route’ originating in Uzbekistan, across the IAMC foothills of Kazakhstan and ultimately reaching Siberia before continuing into Mongolia and China, has been proposed as the most probable scenario for hominin dispersal during glacial and interglacial stages (Li et al., 2019; Zwyns et al., 2019).

These models provide important insights regarding the potential distribution of sites in Central Asia; however, their accuracy is restricted by the qualitative and quantitative characteristics of the input data, i.e., the already known archaeological record (Iovita et al., 2020). Currently, two clusters of Palaeolithic sites are found in the IAMC region of Central Asia. One is in the Russian Altai in the north, and the other one in Uzbekistan in the south. In between, isolated Palaeolithic sites have been found in Kazakhstan, Kyrgyzstan and Tajikistan (Fig. 1). This archaeological picture should be also associated with the uneven distribution of survey and excavation projects in Central Asia. The Russian Altai is the only region that has been researched thoroughly since the 1980s (Derevianko et al., 2018, p. 303), while the low distribution of sites south of the Altai may reflect also the lack of systematic survey work in some of these regions (Fitzsimmons et al., 2017). In addition to this research bias, there is a clear preservation bias in the distribution of Palaeolithic sites in Central Asia, with many Late Pleistocene stratified sites found in caves. Despite their small number, Central Asian caves have yielded a wealth of paleoanthropological remains that led to novel discoveries regarding human evolution, including the identification of the Denisovan hominin group (Krause et al., 2010; Reich et al., 2010; Slon et al., 2018). In this regard, we know little about the formation history of Central Asian sites, since a high-resolution geoarchaeological analysis focusing on formation processes has been applied only in few hominin-bearing caves (Obi-Rakhmat; Mallol et al., 2009a; Denisova cave; Morley et al., 2019). Overall, the current state of knowledge about Late Pleistocene Central Asia is made up of few well-studied sites, extrapolated archaeological models and limited understanding of the formation processes that control the distribution of the archaeological record on a regional scale.

In this context, it is important to note that approximately half of the area of the IAMC falls within the modern borders of Kazakhstan. However, it is not just the sheer size of Kazakhstan that makes it important for studying hominin dispersals, but its geographic location (Fig. 1). In more detail, Kazakhstan is a crossroads for Central Asia, as it constitutes a natural corridor between the cluster of sites in Uzbekistan and the Russian Altai, while it is also connected with China via numerous mountain passes (e.g., the Dzhungarian gate). Complex and tectonically active landscapes, such as the Kazakh piedmonts, would be attractive for Palaeolithic hunter-gatherers since they provide availability of water, shelter, and rich animal and plant resources in contrast to the desert and steppe lowlands that dominate the regional topography (G. N. Bailey & King, 2011; Winder et al., 2015). However, the favorable position of Kazakhstan on the map does not translate to a high density of Late Pleistocene sites. The known stratified sites are Valikhanova (Alpysbaev, 1979; Fitzsimmons et al., 2017; Taimagambetov, 1990, 1997), Maibulaq (Taimagambetov & Ozherelyev, 2008; Taimagambetov, 2009; Fitzsimmons et al., 2017) and Rahat (Dzhasybaev et al., 2018; Ozherelyev et al., 2019), which are open-air loess sites, Ushbas cave (Grigoriev & Volkov, 1998, 2007) and Bukhtarma cave (Gokhman, 1957), with the latter now being flooded, as well as Ushbulaq (Anoikin et al., 2019) and Buirekbastau-Bulaq (Kunitake & Taimagambetov, 2021), which are associated with springs. All of the aforementioned sites have an Upper Palaeolithic age, but detailed data regarding the timing of human occupation come only from loess sites. Based on their work in Valikhanova and Maibulaq, Fitzsimmons et al. (2017) demonstrated that hominin occupation in the Central Asian piedmont may be broadly correlated with environmental changes and continues until the initial stages of the LGM despite adverse climatic conditions. These findings provide a promising basis for investigating further the interplay between human occupation and the semi-arid environment of Kazakhstan. Furthermore, the intriguing lack of more stratified Late Pleistocene sites in Kazakhstan compared to neighboring Uzbekistan and Russian Altai, necessitates a better understanding of the processes that influence site formation and preservation in different Central Asian geomorphic contexts.

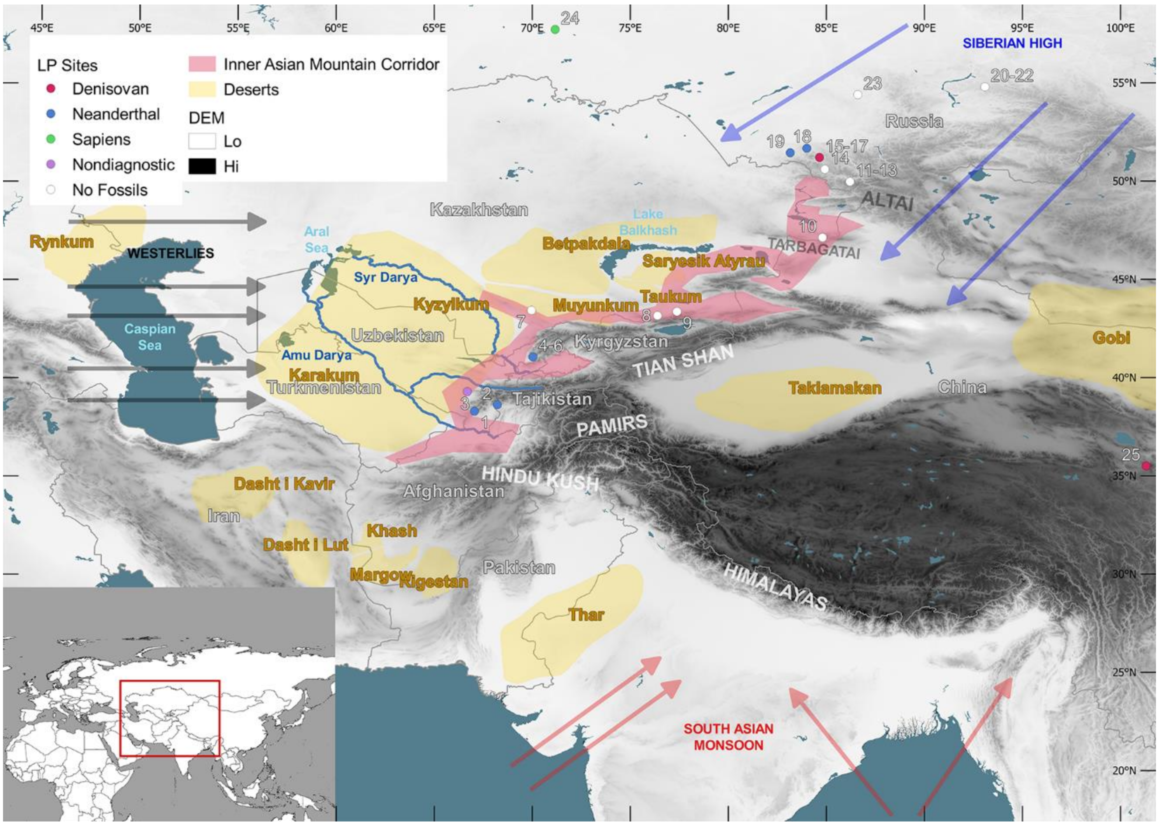

Figure 1. Late Pleistocene sites in and around Central Asia, shown in relation to major topography, deserts, and the area of the proposed Inner Asian Mountain Corridor (IAMC). Also shown is the opposition of the Westerlies to the seasonal weather systems of the Siberian High-Pressure System and the South-Asian Monsoon. 1) Teshik-Tash, 2) Khudji, 3) Anghilak, 4–6) Kulbulak, Obi Rakhmat, Katta Sai, 7) Valikhanova, 8) Maibulak, 9) Rahat 1, 10) Ushbulaq, 11–13) Malo Yaloman, Kara-Bom, Kara-Tenesh, 14) Ust'-Kan, 15–17) Denisova, Ust-Karakol 1, Anui, 18) Okladnikov Cave, 19) Chagyrskaya, 20–22) Ust'-Maltat 2, Derbina 4 & 5, 23) Mokhovo 2, 24) Ust'-Ishim, 25) Xiahe. Data sources: Global Administrative Areas (GADM) (Hijmans, 2012), vector and raster map data from Natural Earth (naturalearthdata.com) and Shuttle Radar Topography Mission (SRTM) Version 4 (Jarvis et al., 2008). **Figure from Paper I**.

1.3.2. Exploring low-density sites in rich archaeological contexts: the Swabian Jura

The archaeological record of the Swabian Jura, south Germany, constitutes a point of reference for human evolution worldwide due to the presence of numerous Palaeolithic sites with rich material culture including organic artifacts, artwork, musical instruments and ornaments (Conard, 2003; Conard & Bolus, 2006; Barth et al., 2009; Conard et al., 2009; Wolf & Conard, 2015; among others). Palaeolithic assemblages in the Swabian Jura are mostly found in caves and rockshelters spanning the Middle Palaeolithic, the Aurignacian, the Gravettian and the Magdalenian (Conard & Bolus, 2003, 2008; Higham et al., 2012; Conard, 2015; Bolus, 2015; Conard, Bolus, et al., 2015). However, the distribution of Palaeolithic sites in the region is not uniform. Caves and rockshelters with long occupational sequences that have been used to establish the regional cultural and chronological stratigraphy are clustered in the Ach and Lone valleys (e.g., Hohle Fels and Geißenklösterle; Conard & Bolus, 2003, 2006, 2008; Higham et al., 2012; Bataille & Conard, 2018; Taller & Conard, 2019; Vogelherd; Conard et al., 2003; Niven, 2006; Hohlenstein-Stadel; Peyrégne et al., 2019; Kind, 2019; Richard et al., 2020). On the other hand, other valleys of the Swabian Jura, such as the Lauchert, are characterized by fewer sites with more ephemeral occupation (Toniato, 2021).

Based on this research background, the interplay between settlement patterns, site use and occupational intensity has been investigated thoroughly in the Ach and Lone valleys. Zooarchaeological data suggest that occupational intensity varies among sites (Boger et al., 2014) and some caves appear to have more punctuated human presence as they also functioned as hyena or cave bear dens, especially during the Middle Palaeolithic (e.g., Große Grotte, Münzel & Conard, 2004b; Hohlenstein-Stadel, Kitagawa, 2014, p. 204, Kogelstein; (Ziegler in Böttcher et al., 2000; Conard, et al., 2015). Overall, more intense human occupation in the region is documented during the Upper Palaeolithic, with zooarchaeological data suggesting seasonal occupation and diverse subsistence strategies between the Ach and Lone valleys. In more detail, the Ach valley shows greater anthropogenic input in comparison to the Lone (Kitagawa, 2014, p. 255), especially during the Gravettian (Conard & Moreau, 2004; Moreau, 2010), with repeated occupations during the winter and spring (Münzel & Conard, 2004b). In this respect, human occupation in the Lone valley appears to be scarcer and most probably occurred during the autumn and spring in conjunction with the migration of reindeer (Bertacchi et al., 2021, p. 12; Geiling et al., 2015; Niven, 2007). Despite these differences, refitting artifacts between caves of the Ach valley (Conard & Moreau, 2004, p. 42) and shared material culture between the Ach and Lone (Wolf & Conard, 2015) suggest that caves in both valleys were parts of the same occupation system.

In this context, geoarchaeological analysis targeting formation processes has provided essential insights into the exploration of settlement dynamics and site integrity in the Swabian Jura. Micromorphological analysis in Hohle Fels and Geißenklösterle by Miller (2015) demonstrated that the transition from the Middle Palaeolithic to the Aurignacian reflects limited site use, as suggested by Conard & Bolus (2006), despite variations in geogenic formation processes. Moreover, erosional processes influenced the preservation of archaeological material in both the Ach (Hohle Fels and Geißenklösterle; Goldberg et al., 2003; Miller, 2015) and the Lone (Hohlenstein-Stadel; Barbieri & Miller, 2019; Hornauer-Jahnke, 2019). In this regard, Barbieri et al., (2018, 2021) demonstrated that landscape changes trigger increased cave erosion in the Lone valley, calling into question the assumption of a reduced human presence in the Lone valley compared to the Ach based on lower find densities during the Gravettian (Conard et al., 2012).

The comprehensive multi-disciplinary data presented above provide a vivid picture of Palaeolithic occupation, demonstrating that formation processes enhance the accuracy of prior interpretations. Within this framework, it is necessary to consider how the assessment of settlement dynamics in the Swabian Jura would vary if we incorporated in our analysis localities with a lower archaeological signal. In this regard, it would be interesting to apply a site formation processes approach to investigate the factors that influence find density between the archaeologically poor and archaeologically rich sites of the Ach and Lone valleys. Moreover, an emphasis on the formation history of less studied valleys of the Swabian Jura, like the Lauchert, would provide a necessary step for addressing site and landscape use among different valleys.

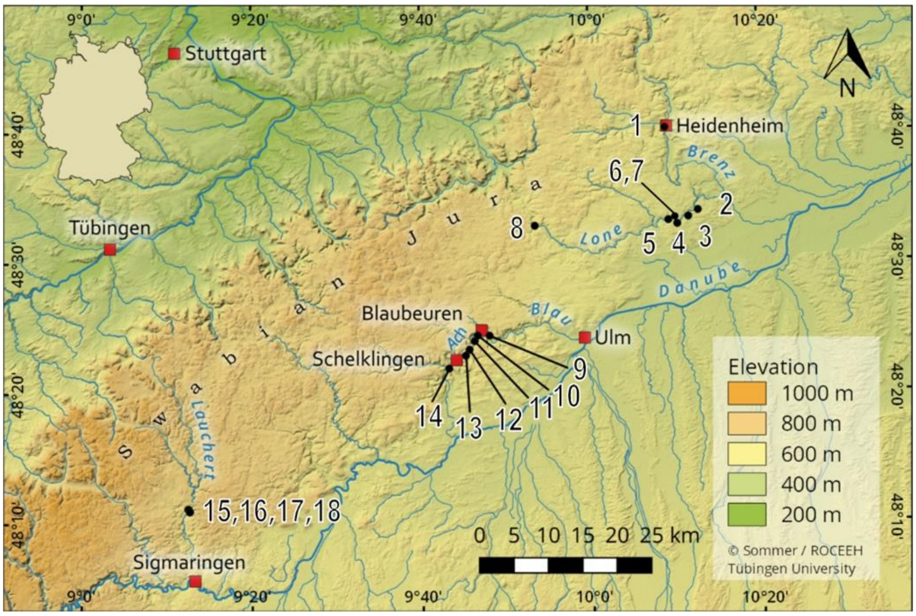

Figure 2. Map of the Swabian Jura showing the location of the Palaeolithic sites of the Lauchert, Ach and Lone valleys. 1) Heidenschmiede 2) Langmahdhalde 3) Vogelherd 4) Hohlenstein-Stadel 5) Bockstein 6) Fetzershaldenhöhle 7) Lindenhöhle 8) Haldenstein 9) Große Grotte 10) Brillenhöhle 11) Geißenklösterle 12) Sirgenstein 13) Hohle Fels 14) Kogelstein 15) Göpfelsteinhöhle 16) Annakapellenhöhle 17) Nikolaushöhle 18) Schafstallhöhle. **Figure from Paper III**.

2. Objectives of the thesis/ doctoral research

The primary objective of this PhD thesis is to investigate the controlling factors that influence the formation history and distribution of Palaeolithic sites in specific archaeological and geomorphological contexts. Its purpose is to use a geoarchaeological methodology that combines the micromorphological analysis of sediments and field data to:

1. Explore the formation processes of individual sites and identify common patterns.

2. Demonstrate how distinct processes influence the overall distribution of the archaeological record in the landscape.

3. Suggest a methodology that could explore the interplay between formation processes and settlement patterns using geoarchaeology

In this regard, this thesis intended to apply a multi-scalar strategy by targeting a regional and a more local scale of analysis developed in two research projects. Each research project addresses a unique set of research objectives outlined below.

Project 1 investigates the relatively understudied Palaeolithic record of Kazakhstan aiming to identify prominent geomorphological contexts for the discovery of new archaeological sites. As part of the PALAEOSILKROAD research program, this project conducted systematic field survey in different key regions of the Inner Asian Mountain Corridor (IAMC) to evaluate the region’s potential for preserving Pleistocene sites. By exploring systematic biases in different geomorphic contexts, we discuss how these biases may influence the types of data that may be extracted by field survey. This methodology aimed to build a framework for future surveys in Kazakhstan and explore the distribution patterns of archaeological sites, which provide the basis for modelling hominin dispersals in Central Asia.

A major component of this project focused on caves and rockshelters since our survey demonstrated that they constitute remarkably promising contexts for the preservation of Pleistocene archaeological sites in our study region (Iovita et al., 2020). This is not surprising since caves and rockshelters have a favorable preservation bias and often provide archives of past human activity worldwide. However, exploring the formation processes of caves and rockshelters in Kazakhstan is of special interest: first, Central Asian caves are scarce but provide a rich fossil record that is commonly used to model hominin dispersals; second, because no prior research has thoroughly assessed the formation processes that may determine the frequency of Palaeolithic caves and rockshelters in the region; third, because geoarchaeological analyses of caves and rockshelters located in similar semi-arid settings are lacking, despite the potential of these regions for hominin dispersals. To discuss these research topics, I focused on the Qaratau mountains, the region with the highest frequency of caves within our study area. In this context, I used a dataset of site-specific excavation data, including micromorphology, and landscape-specific survey data. This multi-scalar approach provides qualitative and quantitative data on the occurrence and type of cave sediments, aiming to explore not only the integrity but also the completeness of the observed record.

Given that our preliminary findings in Kazakhstan demonstrated that the frequency of Palaeolithic sites appears to be relatively low (Iovita et al., 2020; Varis et al., 2022), the second project of this PhD thesis intended to explore the interplay between sites with low find density and settlement patterns. For this reason, *Project 2* employs a more local approach, investigating the sparsely occupied sites of Schafstall II and Fetzershaldenhöhle and the exclusively geogenic site of Lindenhöhle. These sites are located in the Swabian Jura, Germany, a region that is overall characterized by high frequency of Palaeolithic sites. The purpose of the second project was to apply a site-specific approach using micromorphology to address a series of research goals. First, investigate the interplay between the anthropogenic and natural processes that form low-density cave and rockshelter sites. Second, demonstrate the potential significance of low-density sites as records of hominin behavior and paleoenvironment. Third, outline a methodology for investigating sites with limited anthropogenic activity in hunter-gatherer contexts.

3. Materials and methods

Given the multi-scalar approach of this PhD thesis, two distinct research projects were used to investigate different scales of analysis. The materials and methods of the two projects are described in detail in the three respective manuscripts, while a brief summary is presented below.

3.1. Investigating the distribution of Pleistocene archaeological sites in Kazakhstan

Project 1 aimed to investigate the distribution of Pleistocene archaeological sites in Kazakhstan (Paper I and II). This project is part of the PALAEOSILKROAD research program and therefore adopted various methodological aspects convceived by the PALAEOSILKROAD team. The region of interest is the Kazakh part of the IAMC, which comprises the mountain foothills (piedmonts) of the Tian Shan and Altai Mountain ranges that are located within the modern borders of Kazakhstan (**Fig. 1**). Because of the vast extent of the Kazakh IAMC (about 211,500 km^2), the potential study area was reduced to four key regions to provide a realistic and targeted approach. The four key regions are the Qaratau range, the Ili Alatau, the Dzhungarian Alatau and the Altai-Tarbagatai (**Fig. 3**). A brief summary of the geographic setting of the four key regions is provided below, but for a more detailed description see Namen et al. (2020) and Cuthbertson et al. (2021).

- The Qaratau mountain range is located in southern Kazakhstan, delimited by the Syrdarya and Arys rivers to the west, Chu-Sarysu basin and Moyungum desert to the east, South Turgay basin to the north and the western extent of the Tian Shan Mountains to the south. The Qaratau range constitutes a northern segment of the major Talas-Fergana fault, it has a northwest-southeast trend and is divided into two ridges: the Lesser Qaratau in the southeast and the Greater Qaratau in the northwest.

- The Ili Alatau is a northern spur of the Tian Shan range enclosing the depression of the Ili River valley, bounded to the north by the Dzhungarian Alatau and to the south by the Kyrgyz portion of the Tian Shan.

- The Dzhungarian Alatau are located to the southwest of Lake Alakol, enclosing the extensive Dzhungarian Basin that forms a mountain pass known as the 'Dzhungar gates' between Kazakhstan and China.

- The Altai-Tarbagati represents the northern-most study region, encompassing the Kazakh part of the Altai to the north, Tarbagatai mountain range to the south and the basins in between formed by Lake Zaisan and the Irtysh River.

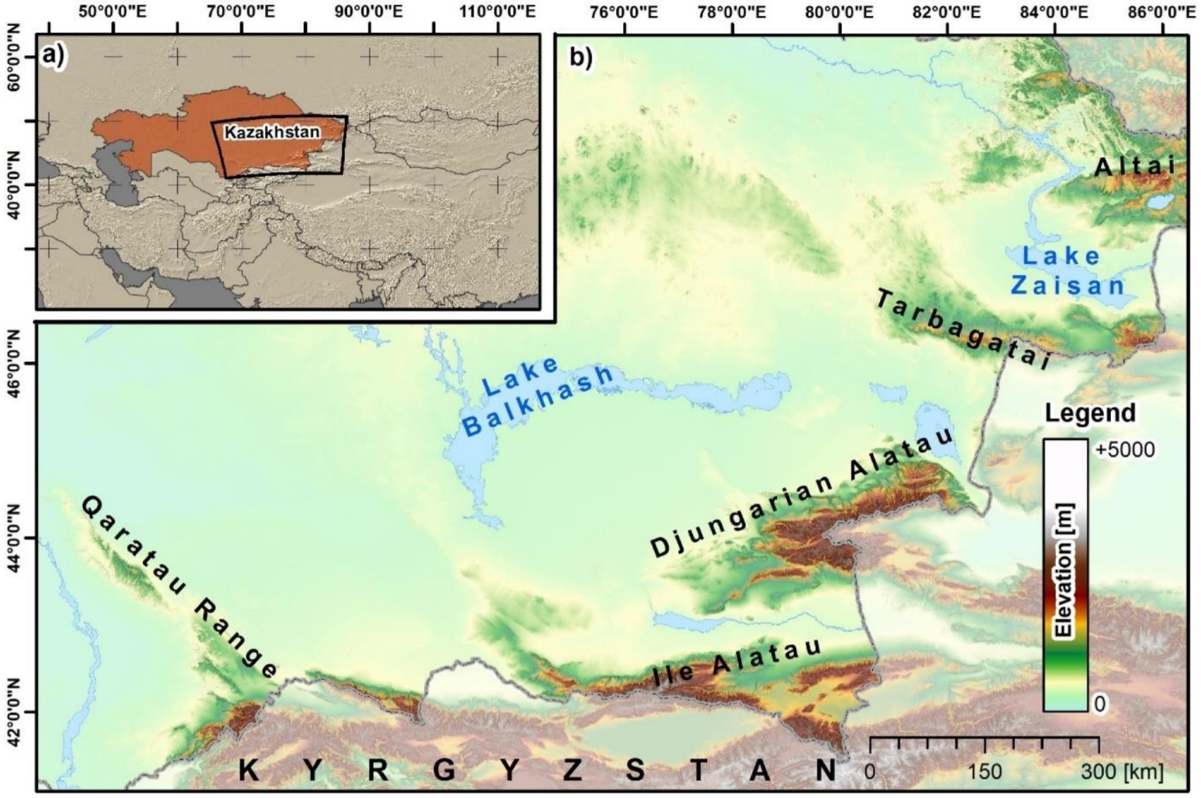

Figure 3. Location and topography of the study area, used from Cuthbertson et al. (2021). A) Location of the study area. B) Terrain Elevation from the ASTER Digital Elevation Model (DEM). Administrative boundaries and waterbodies use copyrighted map data from OpenStreetMap contributors available from openstreetmap.org. Contains data from ASTER GDEM2 (see Cuthbertson et al., 2021, for full information).

This study uses data collected by a systematic field survey conducted across 2017, 2018 and 2019. In 2017, an exploratory field survey was conducted in June and

August focusing on the Altai-Tarbagatai region. In 2018, the survey focused on the Qaratau range from May-June and to the Ili Alatau and Dzhungarian Alatau in August. In 2019, the survey covered the Qaratau, Ili-Alatau and Altai-Tarbagatai areas during May-June and August-September. Archaeological finds were recorded according to different documentation schemes separating individual finds from bulk finds, while a specialized recording schema was developed for fossil material and geological samples. The field survey employed a geoarchaeological approach, aiming to integrate the archaeological finds with their geomorphological context. For this reason, different geomorphological environments were classified (e.g., caves, loess) and a recording strategy was developed to record the geological attributes of promising geomorphological contexts. For more details regarding data structure and data collection see Cuthbertson et al. (2021).

3.2. Investigating the interplay between formation processes and the frequency of cave and rockshelter sites in Kazakhstan

To investigate how formation processes influence the frequency of cave and rockshelter sites in Kazakhstan (**Paper II**), I used the PALAEOSILKROAD dataset of surveyed c/r recorded during the 2017-2019 fieldwork in Kazakhstan (Iovita et al., 2020). This dataset was constructed after a targeted survey of karst forming rocks in the four key study regions, which was structured around a novel predictive modelling approach (Cuthbertson et al., 2021). The model combined unsupervised and supervised landform classification with the near-surface geometry of limestones and carbonates (CERCAMS; Seltmann et al., 2014), to generate predictive mapping areas for regions where karst landforms, such as caves and rockshelters, were more probable to form. Because of the unknown geomorphological record over our study regions and the limited number of already-known Palaeolithic cave sites (*n*=2) that could provide a comparative dataset, we were forced to apply an unsupervised modelling approach during the first model-led fieldwork season (2018). For this unsupervised model we used morphometric features of the ASTER DEM such as elevation, slope, valley depth, slope height and topographic position index (TPI) for different slope positions in local (5km), regional (10km) and global (50km) context. However, in our second fieldwork season (2019) we transitioned to a supervised model based on the survey results that ground-truthed the unsupervised survey of 2018. In our subsequent analyses, we used features found in both unsupervised and supervised models. This predictive modelling approach, combining DEM analysis and field survey, demonstrated that caves and rockshelters in Kazakhstan are typically found in the mid-slope position of steep and high slopes that bound deep valleys (Cuthbertson et al., 2021). The Qaratau mountain range constitutes the most promising region for investigating the formation processes of caves and rockshelters in Kazakhstan, since the overwhelming majority of surveyed caves are clustered in the piedmonts along the mountain front (**Fig. 4**). Therefore, **Paper II** uses the rich cave dataset in the Qaratau mountains to investigate the interplay between formation processes and cave frequency. For a detailed summary of the geology of the Qaratau mountains and its geographic setting in relation to the IAMC see **Paper II**.

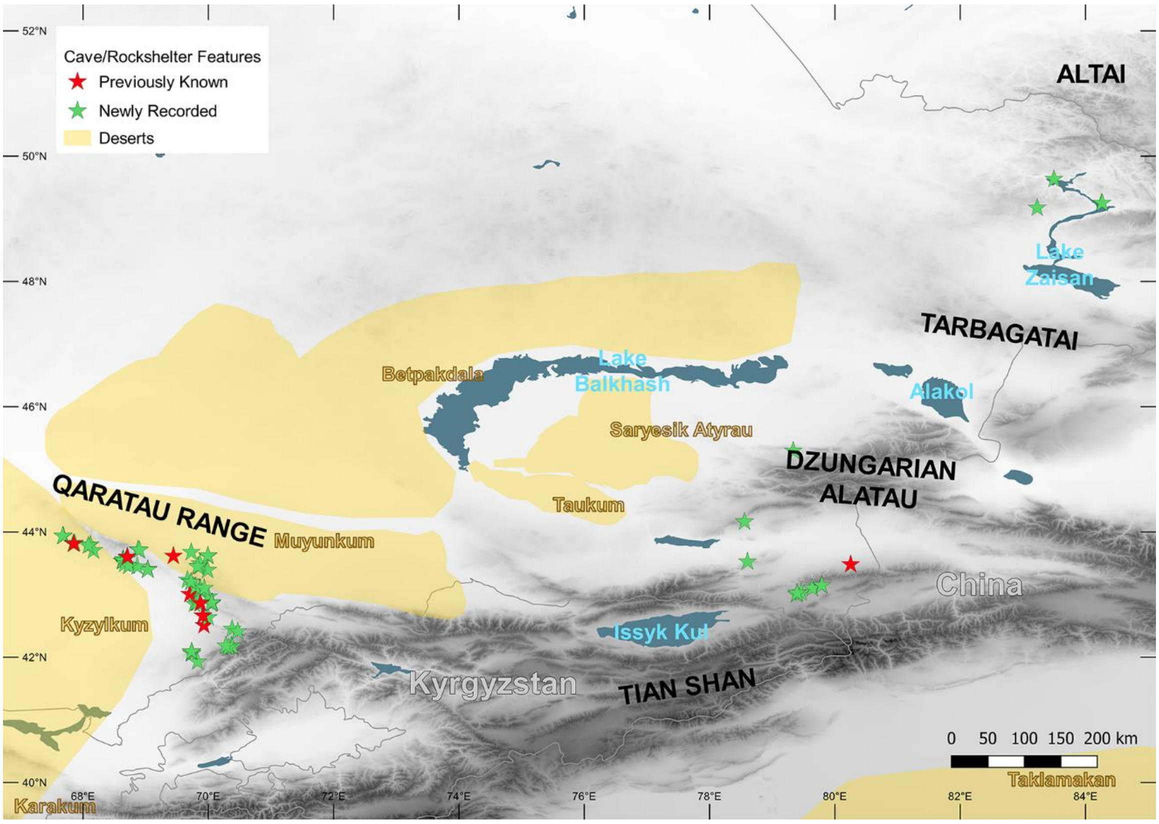

Figure 4. Caves surveyed from the PALAEOSILKROAD team between 2017 and 2019. Includes data from Global Administrative Areas (GADM) (Hijmans, 2012), Natural Earth, naturalearthdata.com, Shuttle Radar Topography Mission (SRTM) Version 4, (Jarvis et al., 2008). Used from **Paper I**.

3.2.1. Site-specific analyses and sediment occurrence

To test the archaeological potential of caves and rockshelters in Kazakhstan, we implemented test-excavations of promising sites in our field survey strategy. For the documentation of the excavated sections and the stratigraphic nomenclature see **Paper II**. In this context, we recorded sediment thickness in individual caves as a proxy for identifying promising sites, expecting that caves with thicker deposits would be more likely to preserve archaeological sediments and Pleistocene archaeology. In unexcavated caves, we have attempted to classify sediment thickness based on field observations of cave morphology and we also used a dynamic cone penetrometer (Kessler Soils Engineering, Inc.; Model K100) to complement our estimations. In excavated caves, we assessed sediment thickness according to published data or from our excavation work. To discuss sediment cover I applied a heuristic classification using three levels; caves with 'Minor' deposits (<0.5m), 'Moderate' (>0.5m) and 'Significant' (>2m). However, the frequency of sediments is also influenced by erosion. In this regard, to explore the impact of erosion in the removal of caves sediments, we identified unique morphological traits that may indicate erosional processes in the inner and exterior areas of the surveyed features (see **Paper II**).

3.2.2. Micromorphology

Regarding site-specific analyses, I used archaeological micromorphology to explore the processes that influence the formation and preservation of the test-excavated sites through time. Micromorphology is an established geoarchaeological technique that studies thin sections of undisturbed sediments to provide a contextual interpretation of the anthropogenic, geogenic and biogenic processes that may lead to the formation of archaeological deposits (Courty et al., 1989; Macphail, 2014; Nicosia & Stoops, 2017). Micromorphology is usually applied in long-term excavation projects involving thorough sampling and often the application of additional microcontextual techniques in the framework of a high-resolution approach (Berna et al., 2012; Milek & Roberts, 2013; Goldberg et al., 2018). In the context of our survey project, we planned for a broad investigation of caves and rockshelters, rather than focusing on a protracted campaign of excavating a single site. Therefore, we used micromorphology selectively to investigate the formation history of particular sites, in order to comprehend complex depositional relationships and investigate the interplay between the site-specific processes and the landscape process monitored during the field survey. Even though this approach was dictated by logistical constraints associated with our prolonged survey campaigns, it provided the opportunity to test how micromorphology can operate in a survey context. For technical information regarding the laboratory processing of block samples, the production of thin sections and the study of thin sections under the petrographic and fluorescent microscope see **Paper II**.

3.3. Investigating low-density occupation sites in respect to regional settlement patterns in the Swabian Jura

To get a better understanding of the formation of low-density sites and explore their role in regional settlement patterns (**Paper III**) I used the well-studied Palaeolithic record of the Swabian Jura as a case study. Specifically, I studied the rockshelter site of Schafstall II in the Lauchert Valley and the cave sites of Fetzershaldenhöhle and Lindenhöhle in the Lone Valley. These sites were selected because they limited to zero anthropogenic activity, were excavated recently with good field documentation and were sampled for micromorphology. The depositional sequence is about 2m thick in all three sites, with geogenic sediments dominating. For a detailed summary of site stratigraphy see **Paper III**.

In Schafstall II, Fetzershaldenhöhle and Lindenhöhle, I used micromorphology to study the diachronic changes in site formation and I especially focused on generating data that would elucidate the interplay between the anthropogenic and natural processes that accumulate deposits. Information regarding the laboratory procedures associated with the processing of micromorphological samples and the production of thin sections can be found in **Paper III**. To contextualize my interpretations, I complemented the micromorphological analysis with field data from the respective sites and the previously excavated archaeological record in the Swabian Jura.

4. Results

4.1. Prominent geomorphic contexts for the preservation and discovery of Pleistocene archaeological sites in Kazakhstan

A major focus of *Project 1* was to identify prominent archaeological contexts for the discovery of new archaeological sites in Kazakhstan. This broad research objective is addressed in **Paper I**, *“In search of a Palaeolithic Silk Road in Kazakhstan*”, based on a systematic survey in four key regions of the IAMC corridor in Kazakhstan between 2017-2019. Our work demonstrated that three geomorphic contexts have the highest probability to preserve archaeological sites; caves and rockshelters, springs and loess. The systematic biases inherent to each geomorphic context and the kinds of data that are extractable by field survey and excavation are presented below.

4.1.1. Caves and rockshelters

During 2017-2019, we have recorded 95 caves and rockshelters in our study regions (**Fig. 4**). The majority of caves and rockshelters have been found in the Qaratau range, with two smaller clusters found in the Jungarian Alatau and Ile Alatau. However, the limited presence of caves and rockshelters in the Kazakh Altai is surprising, given the extended presence of carbonates. Out of the 95 surveyed caves, only 28 contain sediment. Based on field observations and test-excavations, 15 caves and rockshelters preserve evidence of Holocene archaeology, 3 contain Pleistocene archaeology of undetermined age and 4 caves probably preserve sterile sediments of Pleistocene age. To contextualize the archaeological potential of these statistical results, we must explore the processes that influence the formation of caves in Kazakhstan. However, the general characteristics of karst and cave formation in Kazakhstan are poorly known. To our knowledge, the current project is one of the few studies addressing issues of cave formation in Kazakhstan (but see Shakalov, 2010, 2011) and the first one to explore the implications that cave formation has for the preservation of archaeological sites.

First, I present the results on solutional caves, i.e., caves formed by the dissolution of carbonate or non-carbonate rocks by meteoric water (Ford & Williams, 2007).

Extensive cave systems are rare in Kazakhstan and most caves are found isolated without a genetic relationship to modern topography (sensu Frumkin & Fischhendler, 2005). The occurrence of speleothems is limited, which indicates that sediment sequences could be effectively the only archives for retrieving paleoenvironmental data (White, 2007). Tectonics play an important role in cave formation in Kazakhstan with evidence for both brittle and ductile deformation (**Fig. 5A and 5B**), while many caves are associated with fault lines. Occasionally, dislocation of cave walls and extensive breakdown have resulted in significant change of the available cave spaces (e.g., **Fig. 5C**) or led to the formation of depressions that acted as sediment traps (e.g., **Fig. 5D**).

I now turn to pseudokarst caves and rockshelters, which are defined as caves and rockshelters formed in carbonate or non-carbonate rocks by non-solutional processes (Grimes, 1975). In our study region, we demonstrated that caves formed by fluvial erosion in various types of lithologies had the most promising archaeological potential. Caves formed in sandstone have the best likelihood of preserving thick depositional sequences, since sandstone disintegrates by in situ chemical and mechanical weathering that produces autochthonous fine-sand sediments (**Fig. 6B**). Granite rockshelters, on the other hand, are less prone to dissolve into loose sediment, such as grus (Kajdas et al., 2017), and hence less likely to deposit autochthonous sediments that would bury archaeological assemblages (**Fig. 6C**). Pseudokarst caves and rockshelters may also operate as sediment traps for the accumulation of thick aeolian loess deposits, as evidenced by the case of the Nazugum rockshelter (**Fig. 6A**).

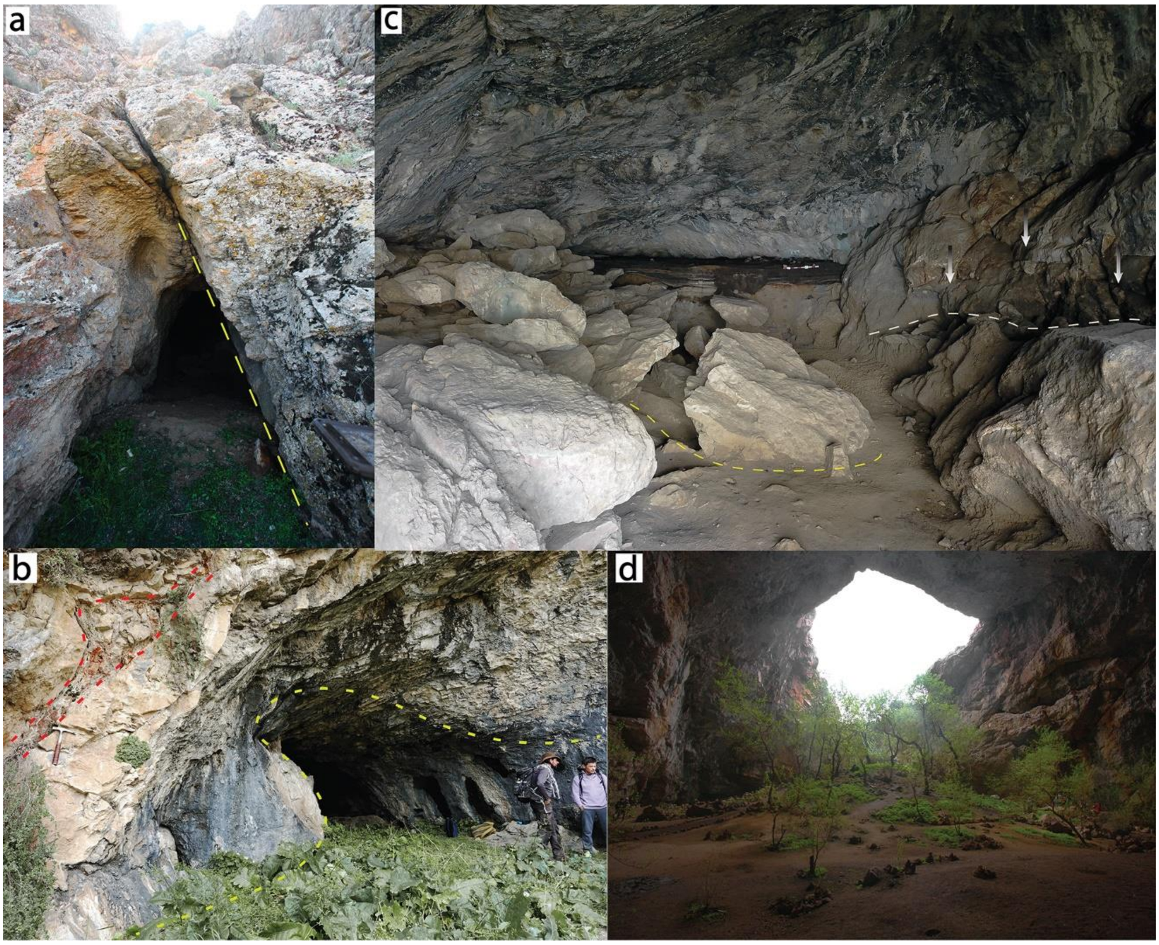

Figure 5. Tectonic processes influencing cave evolution. A) Ushbas. Fault plane of a dip-slip fault (yellow dotted line) indicating the main axis of cave formation. B) Marsel. Asymmetrical fold (yellow dotted line) and tectonic breccia (red dotted line) close to the cave entrance indicate the probable influence of ductile deformation in cave formation. C) Tuttybulaq 1. Extensive slumping in a Bronze Age cave site (Baytanaev et al., 2017, 2018, 2020). Direction of slumping (white arrows) and accumulation of slumped material (white and yellow dotted lines). D) Aqmeshit cave. View towards the collapsed dome at the top part of the cave and the accumulated sediment cone below. Used from **Paper I**.

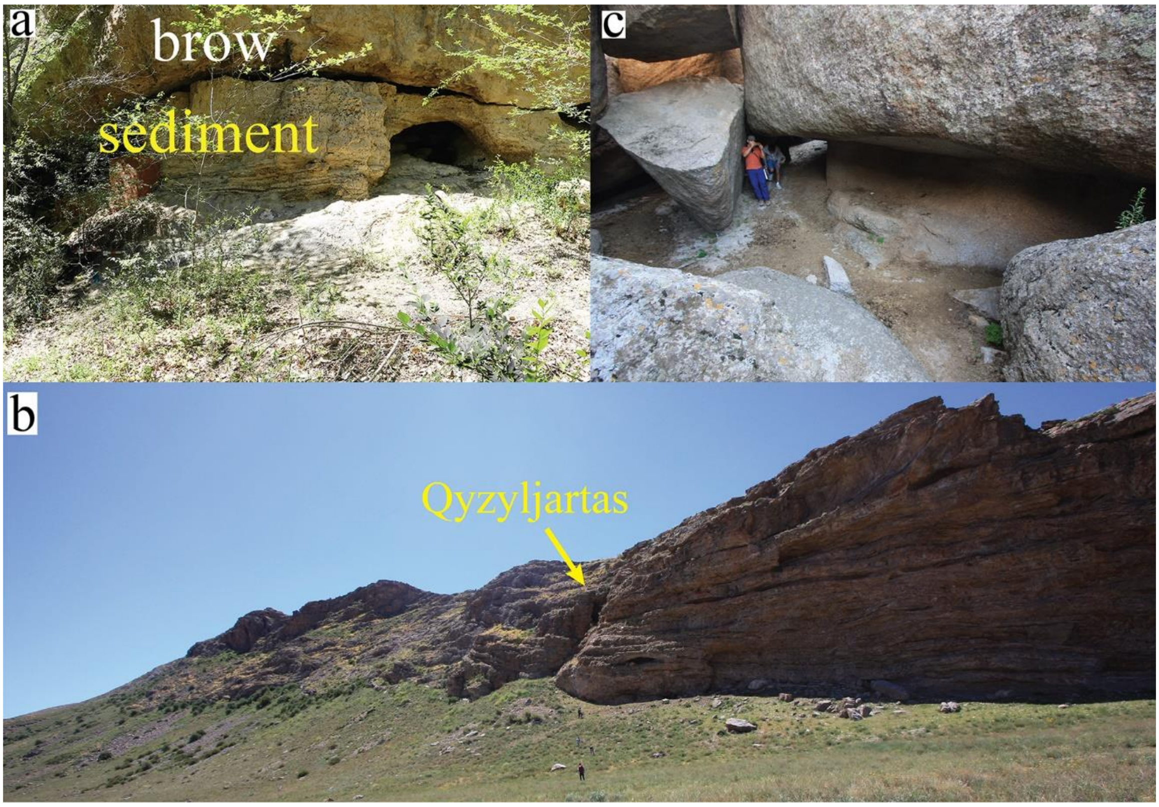

Figure 6. Examples of pseudokarst caves and rockshelters. A) Nazugum rockshelter. Sediments of about 2.5m cover almost entirely the surface of the rockshelter. B) Qyzyljartas cave formed on a sandstone outcrop. C) Black cave. Note the presence of boulder-sized granite blocks but the absence of fine sediment. Used from **Paper I**.

4.1.2. Springs

Springs are favorable targets for a systematic survey. First, they provide resource value to hominins (Cuthbert et al., 2017; Cartwright & Johnson, 2018), especially in semi-arid regions like Kazakhstan. Second, they could precipitate carbonates that cement archaeological deposits and protect them from surface erosion, as in the case of the Koshkurgan Middle Palaeolithic site in Kazakhstan (Derevianko et al., 1999). Third, they provide better archaeological visibility for spotting artifacts on the surface than river valleys, since the composite fluvial/alluvial processes that characterize rivers might lead to the erosion or deep burial of archaeological assemblages (e.g., Blum et al., 1992; Clevis et al., 2006). However, springs have drawbacks as well, since their fluctuating course and ephemeral nature might imply that they are less promising landscape features for the discovery of multi-layered sites along their banks.

Given the association between the formation of springs and tectonic fractures (Kresic & Stevanović, 2010; ch. 2), we focused on the survey of tectonically activated springs located in the Illi Basin and Tarbagatai mountains, following the fault mapping work of Grützner et al. (2019). We discovered and collected surface lithics from various localities along the mountain fronts associated with springs and spring-fed rivers. The lithic assemblages have diverse typo-technological characteristics, indicating possible differences in the chronology of human occupation and site use throughout the history of spring activity.

4.1.3. Loess

The majority of Paleolithic stratified sites in Kazakhstan are found in loess deposits and belong to the Upper Palaeolithic (Valikhanova; Taimagambetov, 1990; Maibulak; Taimagambetov & Ozherelyev, 2008; Rahat; Ozherelyev et al., 2019). These sites appear to be located in similar landscape locations, at the begging of alluvial fans, and have multi-layered occupations. Our rate of success in discovering new loess sites was low, despite our intensive foot survey along specific valleys. Discovering sites in loess is hindered by the thickness of loess deposits, which in our study regions can reach 80 to 100m (Machalett et al., 2006). This implies that older parts of the landscape are buried deeply and cannot be excavated, while loess sites can be identified only in natural exposures or road cuts. In the case of Kazakhstan, Sprafke et al. (2018) demonstrated that the thickness of strata is influenced by the underlying topography, making it difficult to target a certain time period by field-walking near predetermined strata.

4.2. The effect of formation processes in the distribution of caves and rockshelters in Kazakhstan

Paper I demonstrated the potential of Kazakh caves and rockshelters to preserve archaeological sites based on the presence of both Holocene and Pleistocene sediments. However, it also highlighted systematic biases in the occurrence of sediment infills since only 28 out of the 95 recorded caves and rockshelters contain sediments. The second part of research *Project 1* utilized the survey data from **Paper**

I to assess the occurrence of cave and rockshelterrs sediments in our study region and combined site-specific micromorphological data with landscape-specific geomorphological data to explore the formation processes that influence the distribution and preservation of cave and rockeshelters sites in the Qaratau mountains of Kazakhstan. The results of this analysis were published in **Paper II**, "*The effect of formation processes on the frequency of Palaeolithic cave sites in Semi-Arid Zones: Insights from Kazakhstan"*, summarized below.

4.2.1. Sediment occurrence among the surveyed c/r in the IAMC of Kazakhstan

The amount of sediment cover varies among the 28 caves and rockshelters that contain sediments. The classification of sediment thickness in both unexcavated and excavated caves and rockshelters demonstrated that four caves have 'Minor' deposits (<0.5m), ten caves and rockshelters have 'Moderate' (>0.5m) deposits and 14 caves and rockshelters have 'Significant' (>2m) deposits (**Fig. 7A**). Finally, archaeological materials are more likely to be found in caves with thicker depositional sequences (**Fig. 7B**).

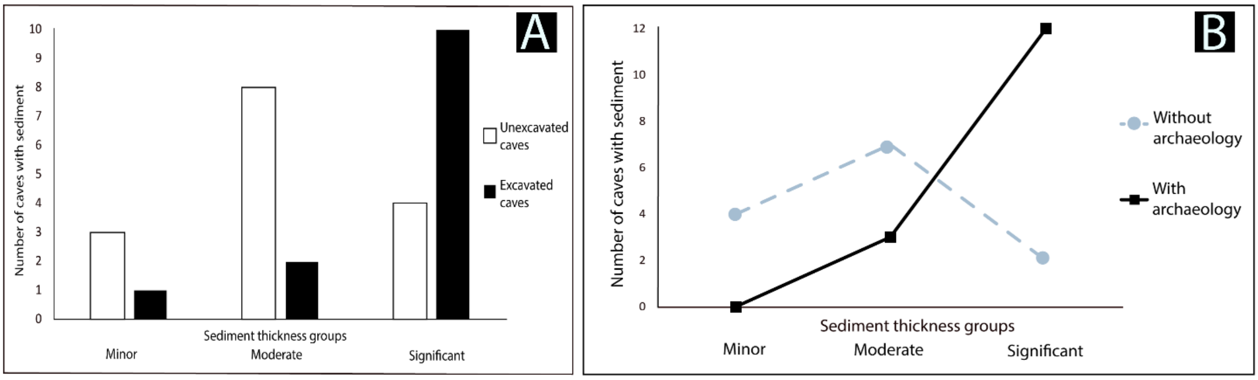

Figure 7. Sediment occurrence among the surveyed caves and rockshelters between 2017-2019. A) Excavated and unexcavated features with sediment (N=28) grouped by sediment thickness. B) Occurrence of archaeology among the different sediment thickness groups. Dotted line: features without archaeology. Solid line: features with Holocene or Pleistocene archaeology. Used from **Paper II**.

4.2.2. Site-specific formation processes in caves and rockshelters of the Qaratau mountains based on micromorphology

To explore the site-specific processes that influence the formation history of caves and rockshelters in Kazakhstan, I used field data based on excavations of test-pits in promising caves and high-resolution data supplied by the micromorphological analysis of the excavated sequences. Five caves of the Qaratau mountains were selected for this analysis (Jetiotau, Qyzyljartas, Ushozen 1, Qaraungir 1, and Aqtogai 1; **Fig. 8**) because their diverse sequences provide an overview of the key processes that influence the formation of caves in the region. Here, I briefly summarize site stratigraphy and micromorphological analysis (**Table 1**) by also providing interpretations of the described depositional characteristics. For the detailed location of caves in the Qaratau mountains and detailed presentation of the analytical results, including excavation and micromorphology descriptions, see **Paper II** and Supplementary Material therein.

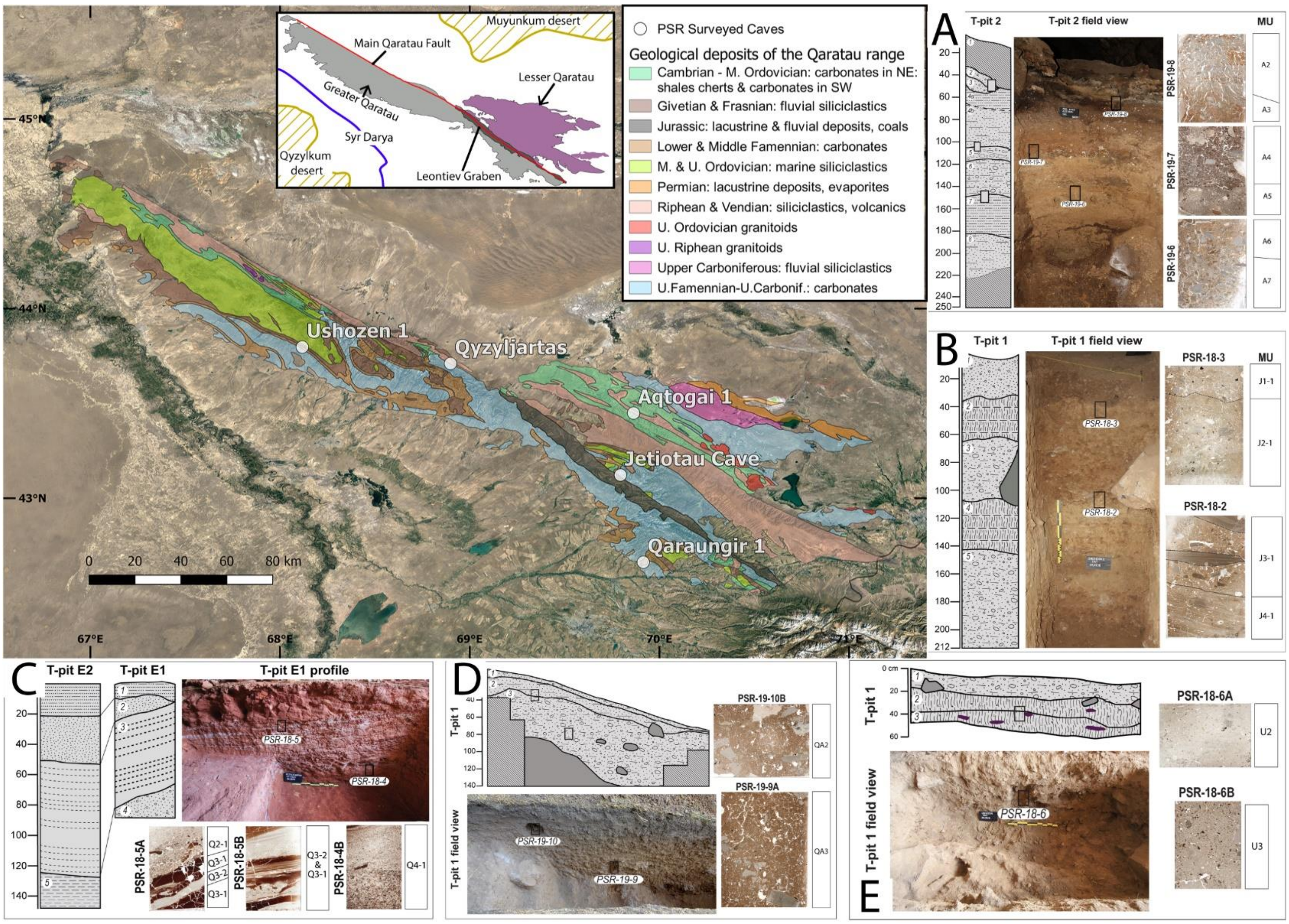

Figure 8. A) Geography and geology of the Qaratau mountains with location of studied sites.

Geological deposits adapted from Alexeiev et al. (2009; Fig. 1). Note the complex piedmont topography along the Qaratau mountain front as opposed to the surrounding deserts and steppe lowlands. Imagery ©2021 TerraMetrics, Qaratau Range Kazakhstan @43.5235,69.2049, https://www.google.com/maps/. Site stratigraphy and micromorphology for Aqtogai 1 (A), Jetiotau (B), Qyzyljartas (C), Qaraungir 1 (D) and Ushozen 1 (E). Adapted from **Paper II**.

Jetiotau cave (**Fig. 8A** and **8B**) has a stratigraphic sequence of 2.12 m separated into 5 lithological units (LUs; J1-J5) without reaching bedrock. The sequence is characterized by an alteration between dark brown clast-rich deposits dominated by limestone fragments and lighter clast-poor deposits. Bone and charcoal fragments were recovered in small numbers spread throughout several LUs, however artifacts such as pottery or lithic tools were absent. Pending OSL dates will provide a chronological constrain for the depositional sequence at Jetiotau.

Site	**Lithostratigraphic Unit (LU)**	**Micromorphology sample**	**Microstratigraphic Unit (MU)**
Jetiotau	J1	PSR-18-3	J1-1
	J2		J2-1
	J3	PSR-18-2	J3-1
	J4		J4-1
	J5	-	-
Qyzyljhartas	Q1	-	-
	Q2	PSR-18-5A	Q2-1
	Q3	PSR-18-5B	Q3-1 Q3-2
	Q4	PSR-18-4	Q4
	Q5	-	-
Ushozen 1	U1	-	-
	U2	PSR-18-6A	U2
	U3	PSR-18-6B	U3
Aqtogai 1	A1	-	-
	A2	PSR-19-8	A2
	A3		A3
	A4	PSR-19-7	A4
	A5		A5
	A6	PSR-19-6	A6
	A7		A7
	A8	-	-
Qaraungir 1	QA1	-	-
	QA2	PSR-19-10	QA2
	QA3	PSR-19-9	QA3

Table 1. Summary table for correlating cave sites, lithostratigraphic units (LUs), micromorphology samples and microstratigraphic units (MUs) for caves of the Qaratau mountains. Adapted from the supplementary material of **Paper II**.

Microstratigraphic unit **(MU) J4-1** has a laminated structure indicative of sheetwash processes in a low energy water-lain environment (Mücher & Ploey, 1977). However, phases of non-saturation are evidenced by intrusive dusty clay coatings, burrows and planar voids indicating wetting and drying cycles (**Fig. 9A**).

MU J3-1 is a heterogeneous clast-supported deposit comprised primarily of geogenic material. Laminated clasts that probably represent remobilized material originating from the cave interior are common (**Fig. 9B**). Biogenic inclusions include phosphatized pellets, carnivore coprolites and bones. Based on the inclined geometry, unsorted sediment, preferential concentration of coarse clasts and the presence of vesicles and deformation features (**Fig. 9C**), I interpreted **MU J3-1** as a relatively fluid debris flow (Karkanas & Goldberg, 2018a). The pre-existing inclined sloped surface of LU J4 may provide the necessary angle for the formation of a debris flow. In this context, slumped laminated clasts indicate that topographic variation and inclined surfaces probably characterized the geometry of sediments farther within the cave (**Fig. 9B**). **MU J2-1** has a similar groundmass to MU J3-1 but contains charcoal fragments and has a granular microstructure. The micromass is characterized by a variety of phosphatic, de-calcified and cemented patches reflecting a mixture of different sediment sources (**Fig. 9D**). **MU J1-1** corresponds to modern cave use, has a similar fabric with MU J2-1 and is bioturbated.

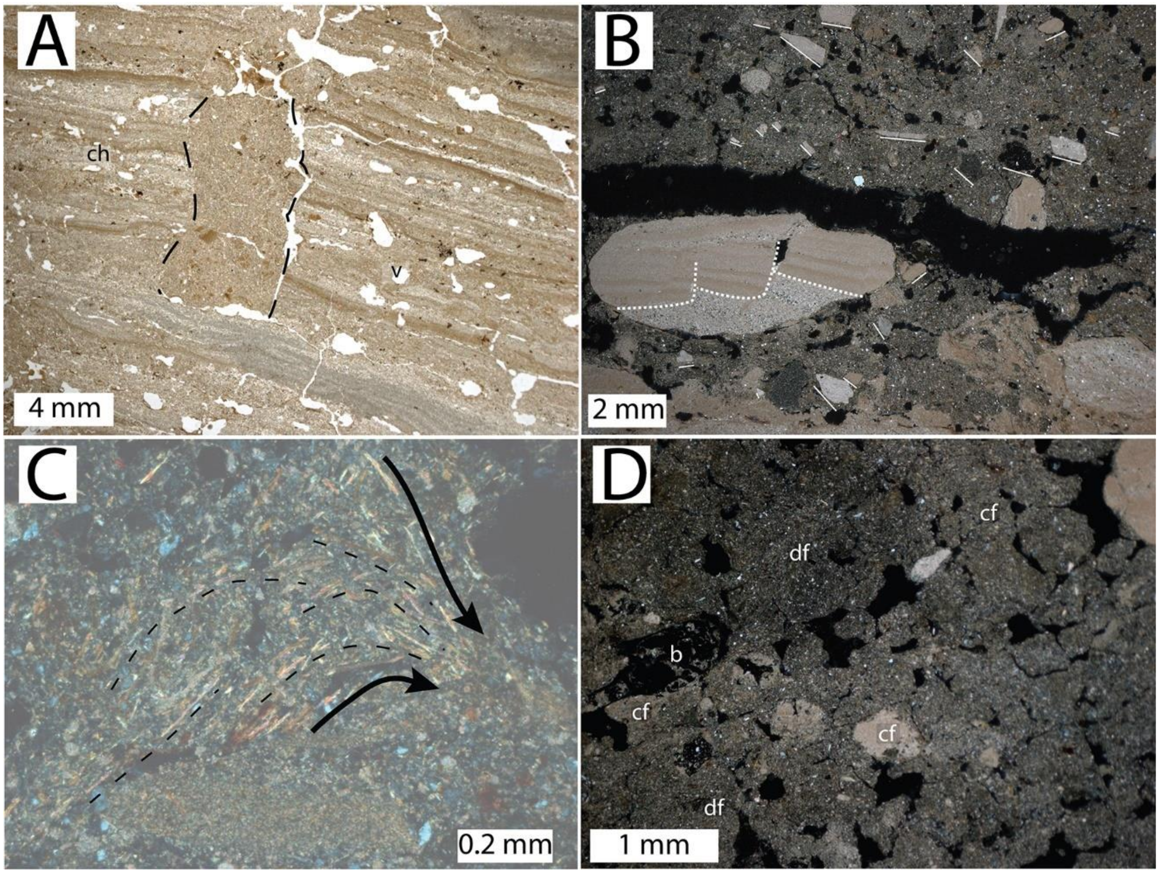

Figure 9. Microphotographs from Jetiotau cave. A) MU J4-1; Note laminated bedding dipping towards SW and complex microstructure consisting of vesicles (v) and channels (ch). Dotted lines outline a burrow breaking through laminae; PPL. B) C) MU J3-1; Note oblique to horizontal orientation towards the SW for the majority of coarse clasts (white lines). White dotted lines indicate slumping of a laminated clast; XPL. C) MU J3-1; Photomicrograph and sketch of a rotational micro-deformation feature showing preferential distribution, orientation and alignment of mica particles. Dotted and solid lines indicate general flow direction; XPL. D) MU J2-1; Mixing of calcitic crystallitic aggregates and matrix (cf) with decalcified and phosphatized (df) b-fabric. A partially cemented bone fragment (b) is also present; XPL. Adapted from **Paper II**.

Qyzyljartas cave (**Fig. 8A** and **8C**) has a stratigraphic sequence of 1.5m until bedrock. It is composed of geogenic components of fluvial origin alternating between clast-supported deposits rich in sands and gravels and matrix-supported deposits with a clayey texture. Redox-depleted horizons formed by settling water (pseudogleying) characterize LU Q3, while an erosional contact separates LU Q3 from LU Q2. During section cleaning a single lithic artifact of unknown industry was found, although its stratigraphic placement is uncertain. The fluvial sequence discovered in Qyzyljartas cave is approximately 20m above the contemporary river floor, most probably representing an earlier phase of valley formation. This would imply a potential Pleistocene age for the Qyzyljartas sequence, which will be explored further with a pending OSL date from LU Q2.

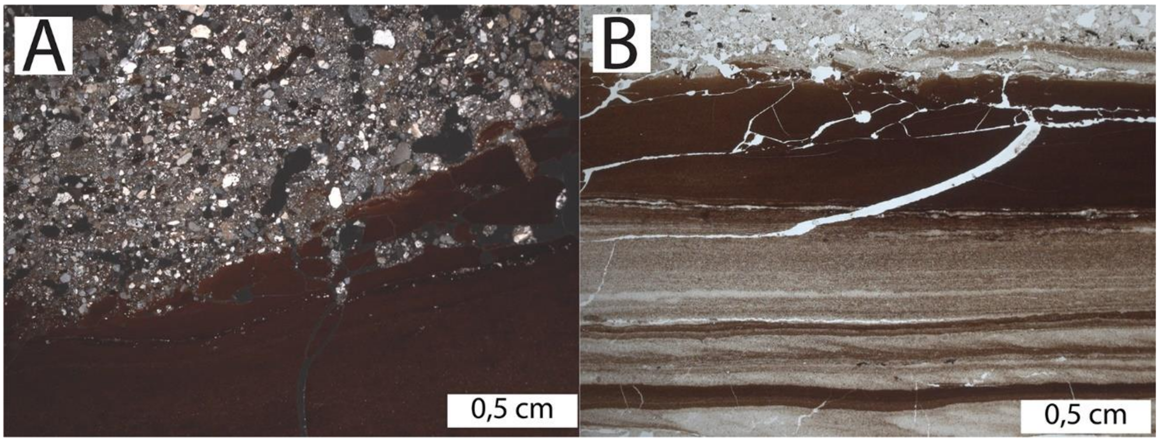

Figure 10. Microphotographs from Qyzyljartas. A) Sharp and probably erosional boundary between MU Q2-1 and MU Q3-1; XPL. B) Interbedded MU type Q3-1 (silty clay) and Q3-2 (sand) layers; PPL. Used from **Paper II**.

MU Q2 is a clast-supported deposit rich in rounded quartz, sandstone and shale rock fragments. The large size and rounded shape of the coarse material indicate high-energy water action and long transport distances. Rip-up clasts and a sharp boundary demonstrate the erosion of the underlying layer LU 3 (**Fig. 10A**). LU Q3 is made of two interbedded MUs, **MU Q3-1**, a matrix-supported layer of clayey texture, and **MU Q3-2**, a clast-supported layer with abundant quartz grains and lack of clay (**Fig. 10B**). **MU Q3-2** exhibits normal or reverse grading indicating changes in sedimentation. **MU Q4** has a similar fabric with **MU Q2-1** but has a higher clay content and demonstrates normal grading.

Ushozen 1 cave (**Fig. 8A** and **8E**) has a shallow stratigraphy of about 60cm divided into three LUs (U1-U3). The deposits have a sandy silt texture with a low amount of coarse components, suggesting the accumulation of wind-blown sediments. In **LU U3**, we recorded abundant manganese oxide nodules probably originating from the parent rock. In **LUs U1** and **U2** we found Bronze Age archaeological materials suggesting a Late Holocene age for the deposition of these units.

MU U2 and **MU U3** show a bimodal distribution comprised mainly of manganese oxide nodules, silty clay clasts originating from reworked endokarstic sediments (e.g.

Goldberg et al., 2015, p. 623) and rock fragments in a loess matrix (**Fig. 11A**). **MU U3** is more bioturbated, while **MU U2** contains soil aggregates, often phosphatized (**Fig. 11B**). The homogeneous loess matrix in both MUs confirms the influence of aeolian processes in the accumulation of cave sediment, as hypothesized in the field. The lack of upslope soil cover indicate that the soil aggregates were most probably trampled into the cave by humans (Goldberg et al., 2009). The phosphatization of soil material however demonstrates burial and remobilization of materials in the cave environment, demonstrating reworking of the 'primary' loess matrix.

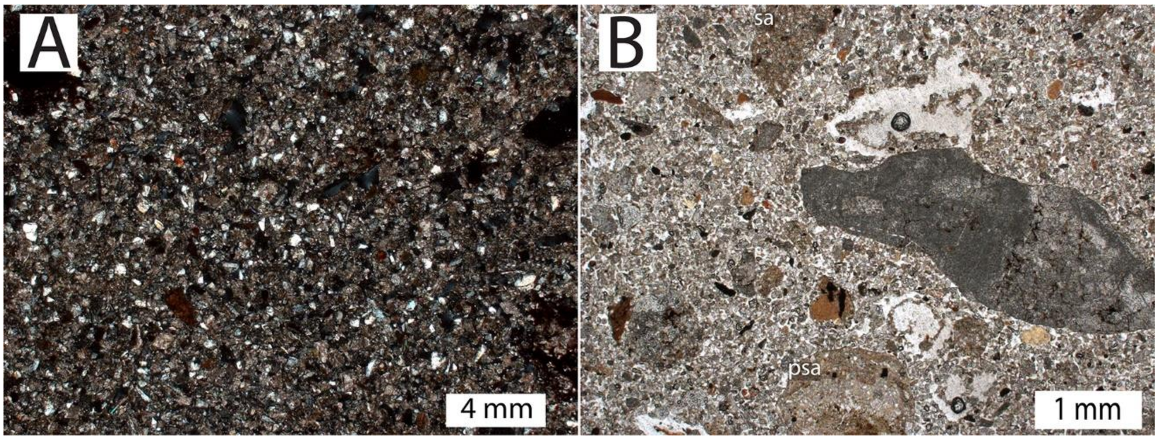

Figure 11. Microphotographs from Ushozen 1 cave. A) Both MUs are comprised of well sorted quartz and mica grains in a calcitic crystallitic micromass, indicative of loess deposits; XPL. B) MU U2; sand-sized rounded soil aggregates (sa), some of which are phosphatized (psa) demonstrate variability in post-depositional processes; PPL. Adapted from **Paper II**.

<u>Qaraungir 1</u> (**Fig. 8A** and **8D**) cave has a depositional sequence of about 140cm in the slope area in front of the cave, incorporating scarce Holocene archaeological material. In this regard, our work in the exterior of the cave and the work of Taimagambetov & Nokhrina (1998) in the interior of the cave, suggest that the sediments of Qaraungir 1 were most probably deposited during the Holocene. The LUs have a silty clay texture with a high frequency of coarse clasts.

MU QA3 and **QA2** are both clast-supported deposits that consist of both geogenic and biogenic sediments in a micromass characterized by a strong aeolian component (**Fig. 12B**). The coarse clasts have a uniform orientation following the inclination of the slope (**Fig. 12A**), while fabric hypocoatings around the coarse grains constitute another proxy of grain mobilization (**Fig. 12B and 12C**). The presence of phosphatic grains and the development of phosphatic rinds around limestone clasts suggest that this material was originally deposited in the interior of the cave and eroded into the slope area (**Fig. 12B, 12C and 12D**). This remobilization of material demonstrates the presence of colluvial eroding processes in the Qaratau caves.

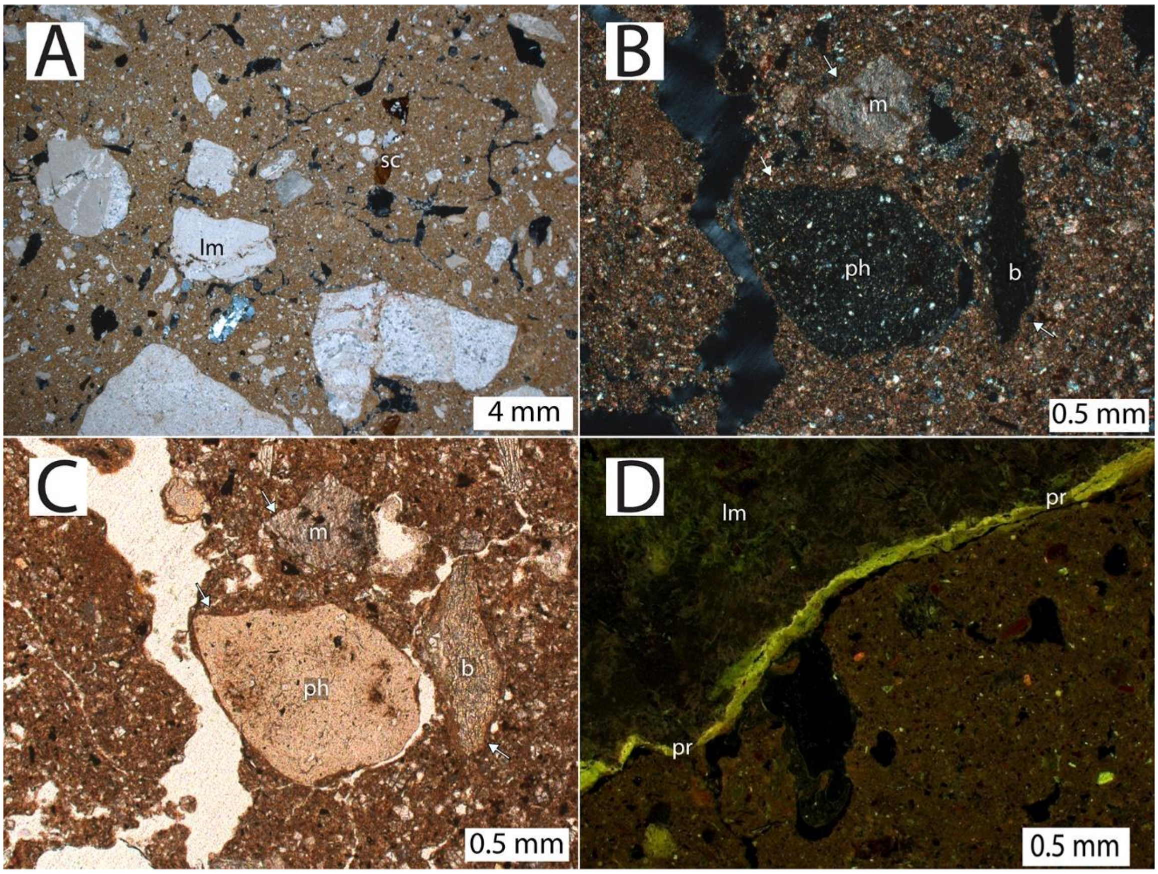

Figure 12. Microphotographs from Qaraungir 1 cave. A) MU QA3; A comparison of the grain size and sorting between coarse components (e.g., limestone (lm) or silty clay (sc) clasts) between the lower left and top right part of the microphotograph constitute an example of microlayering, probably as a result of colluvial movement; XPL. B) MU QA2. Closer view of the calcitic crystallitic b-fabric, rich in quartz and mica, that characterizes the groundmass of both samples. Fabric hypocoatings (white arrows) around coarse clasts (phosphatized grain; ph, marble; m, bone; b) demonstrate reorientation of fabric by mechanical forces (Stoops, 2003, p. 112); XPL. C) Same as B but in XPL to demonstrate isotropic fabric of phosphatic grain. D) MU QA2; Phosphatic rind (pr) around limestone (lm) in an organic-rich matrix. Adapted from **Paper II**.

Aqtogai 1 cave (**Fig. 8A** and **8B**) has a stratigraphic sequence of about 2.5m without reaching bedrock. The lower half of the sequence is more clast-supported with limestone fragments, while matrix-supported layers with calcite and clay nodules characterize the upper part of the sequence. The topmost deposits were grouped as LU A1 since they consist of interbedded organic-rich and humified layers associated most probably with fumier/stabling deposits (Macphail et al., 2004; Brönnimann, Ismail-Meyer, et al., 2017; Shahack-Gross, 2017). The upper part of the sequence is of Holocene age based on the presence of pottery, but dung pellets found in the micromorphological analysis of LU A7 (see below) demonstrate that the lower parts of the sequence are also of Holocene age.

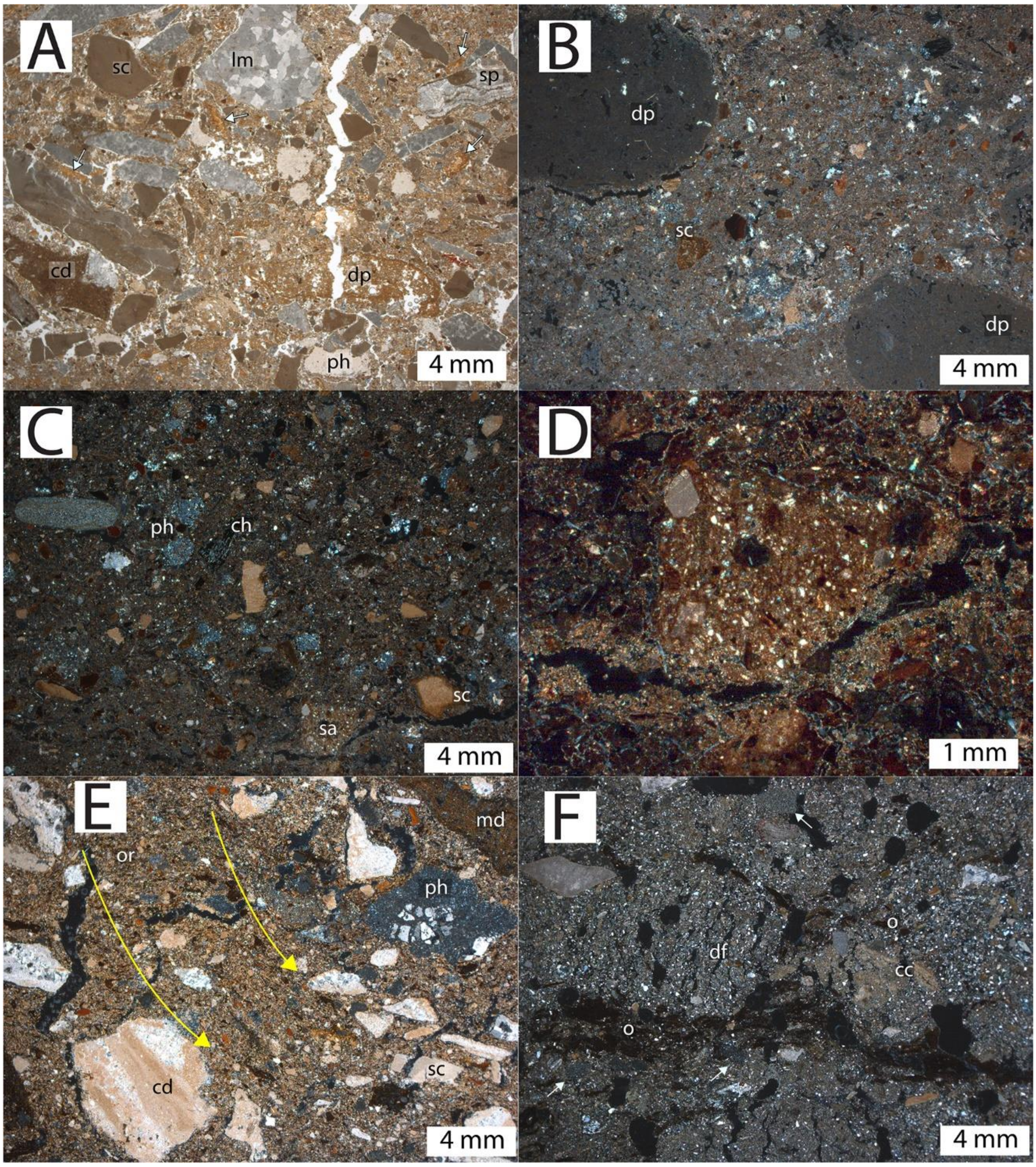

Figure 13. Microphotographs from Aqtogai 1 cave. A) MU A7; limestone fragments (lm) and silty clay clasts (sc) mixed with dung pellets (dp), degraded dung (arrows) and phosphatized material (ph). Cemented deposits (cd) and a speleothem fragment (sp) are also present indicating the mixing of heterogeneous deposits; PPL. B) MU A5; dung pellets (dp) and silty clay clasts (sc) embedded in an ashy matrix; XPL. C) MU A4; charcoal (ch), sediment aggregates (sa) and isotropic phosphatic aggregates (ph); XPL. D) Microphotograph of the soil-aggregate indicated in D. Note the high concentration of quartz silt/sand in the aggregate in contrast to the surrounding groundmass. XPL. E) MU A3; Limestone fragments, cemented deposits (cd) and silty clay clasts (sc) mixed with phosphatic aggregates (ph) and massive dung (md) remains in an organic rich (or) matrix. Coarse material is preferentially distributed and oriented along planes (yellow arrows); XPL. F) MU A2; calcitic crystallitic aggregates (cc) and phosphatized (white arrows) aggregates mixed with decalcified matrix (df). Notice organic laminations (o); XPL. **Used from Paper II**.

MU A6 and **MU A7** are clast supported deposits made of geogenic materials and major dung input. Dung is found in different stages of preservation, which suggests sediment mixing (**Fig. 13A**). However, oriented coarse materials that could indicate the presence of colluvial processes reworking the deposits are only recorded in **MU A7**. **MU A5** is dominated by gravel-sized dung pellets (**Fig. 13B**). **MU A4** shows similarities to fumier/stabling deposits based on the presence of charcoal, dung, authigenic gypsum and organics (Macphail et al., 2004; Brönnimann, Ismail-Meyer, et al., 2017; Shahack-Gross, 2017). The presence of reworked cave materials, biogenic inclusions and soil aggregates demonstrate the interplay of different sediment sources in the formation of this deposit (**Fig. 13C and 13D**). **MU A3** is a coarse heterogeneous deposit made of numerous rock fragments, silty clay clasts and dung pellets in a diverse state of preservation like **MU A6** and **A7**. The coarse material shows uniform dipping and is microlayered indicating colluvial processes (**Fig. 13E**). **MU A2** is the only matrix-supported deposit recorded in the sequence. It has a high silt/fine sand quartz and mica content indicating increased aeolian sedimentation and discrete laminations of organic matter (**Fig. 13F**). Aeolian sedimentation and organic laminations indicate slow deposition rate and preservation of original sediment structures.

4.2.3. Landscape-specific formation processes in caves and rockshelters of the Qaratau mountains

To complement the results of the site-specific micromorphological analysis, I used geomorphological data gathered during field survey to investigate how sedimentation and erosion influence the formation history of caves and rockshelters on a landscape scale.

Field survey provided minimum evidence for the erosion of sediments in individual caves, with potentially older cave surfaces recorded in few caves and rockshelters (**Fig. 14A and 14B**). Erosion is more typically associated with processes monitored in the exterior of c/r. In more detail, caves and rockshelters in the Qaratau mountains are usually found in a mid-slope position (Cuthbertson et al., 2021) overlooking erosional landforms, such as scree-slopes and talus cones (**Fig. 14C**). The formation of erosional scree-slopes is common in semi-arid environments like Kazakhstan

(Abrahams et al., 1994), which could indicate that caves or cave sediments might have been eroded from the landscape. Also, the absence of caves and rockshelters at the bottom of slopes and valley systems may imply the masking of pre-existing landforms by the accumulation of scree or loess. Large scale erosion and rockfall has also been observed in the front part of the caves, probably as a result of active tectonics (**Fig. 14D** but see also **Paper I**).

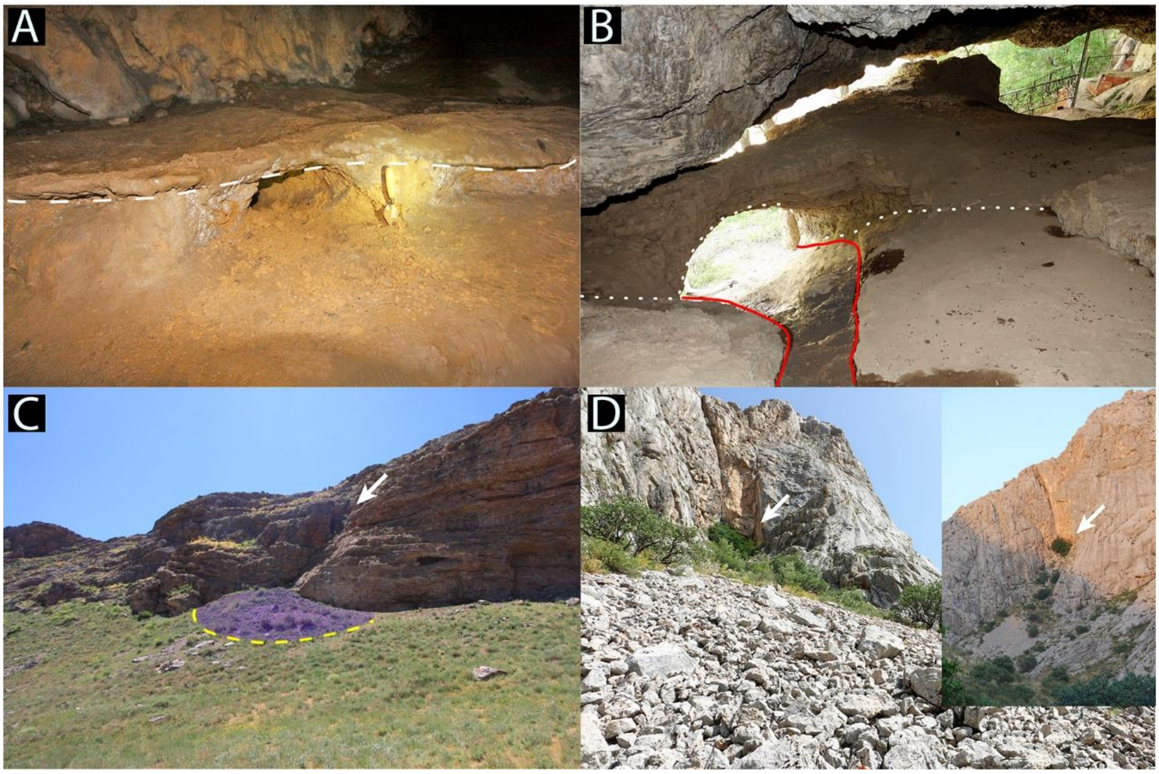

Figure 14. Erosional processes in the interior and exterior of caves and rockshelters. A) Truncated flowstone surface and underlying clayey deposits (contact marked with white dashed line) in Jetiotau cave. B) Active erosion in Nazugum cave. Water channel (red solid line) cutting through sediment cover (white dotted lines). C) Talus cone (yellow dashed line) below the entrance of Qyzyljhartas (arrow) demonstrates near-entrance collapse. D) Tuttybulaq 2 (white arrow) provides an example of caves located in mid-slope position, overlooking scree slopes. **Used from Paper II**.

4.3. Exploring the formation processes of low-density sites in the Swabian Jura

A major focus of research project 2 was to explore the formation processes of low-density sites found in regions with rich Palaeolithic occupations. This research objective is addressed in **Paper III**, *“Using formation processes to explore low-density sites and settlement patterns: a case-study from the Swabian Jura”*, based on the geoarchaeological analysis of the low-density sites of Schafstall II and Fetzershaldenhöhle and the archaeologically sterile site of Lindenhöhle. The results, combining micromorphological analysis and field data (**Table 2**), are briefly summarized below, along with interpretations (**Fig. 15**). For a detailed description of micromorphological thin sections and a synthesis of formation processes, see **Paper III**.

4.3.1. Site formation processes in Fetzershaldenhöhle, Lindenhöhle, and Schafstall II

The lowest unit at **Schafstall II** (GH 6/ **MU SS1)** is a purely geogenic sediment dominated by laminated aggregates suggesting deposition under phreatic cave conditions. An erosional contact marks the transition to sub-aerial conditions associated with the lower part of GH 5 (**MU SS2**), based on the presence of biogenic materials such as carnivore, coprolites, phosphatic aggregates and bones that have been reworked by freeze-thaw processes. Minimum hominin presence is also recorded based on the presence of few burned bones in thin section and in the field. The upper part of GH 5 and GH 4 (**MU SS3**) have a higher content of biogenic input, while the deposits have most probably accumulated under warmer and moister conditions based on the high abundance of clay pedofeatures and diagenetic processes, such as phosphatization. GH 3, 2c, 2b and Hf have been classified as **MU SS4**, but their formation processes vary slightly in comparison to **MU SS3**. **MU SS4** is as well characterized by increased carnivore activity, while anthropogenic activity is reported but limited as in the case of **MU SS1**. The formation processes that characterized the sequence from GH 5 to GH 2b change abruptly with the transition to GH 2a (**MU SS5**). GH 2a (**MU SS5**) overall reflects cold and dry conditions based on the presence of homogeneous loess and absence of biogenic inclusions, pedoforeatures and diagenetic processes.

The lowest unit at **Fetzershaldenhöhle** (GH 3 (lowest)/ **MU FH1**)) is a cryoturbated deposit rich in phosphatic grains, including carnivore coprolites, and bones. The upper part of GH 3 (**MU FH2**) is most probably with a roof collapse event based on the presence of angular limestones that comprise >80% of the groundmass. **MU FH3** covers the transition between GH 3 and GH 2 and shows evidence of mass movement based on the presence of galaxy structures. **MU FH4** is a homogeneous loess-rich sediment that shows limited evidence of reworking based on the presence of phosphatic-rich inclusions.

The lowest unit at **Lindenhöhle** (GH 4/ **MU LH1**) is dominated by laminated aggregates associated with reworked karstic sediments and phosphatic grains indicating biogenic deposition, probably related to animal activity. **MU LH2** (lower part of GH 3) is a coarser variation of **MU LH2** that is separated by **MU LH3** (upper part of GH3) with an erosional boundary. **MU LH3** is a heavily cryoturbated deposit made of a reddish clay-rich sediment and a silty brown sediment. **MU LH4** is a homogeneous loess-rich layer without reworked inclusions or phosphatic sediment and a high content of clay pedofeatures indicating moist conditions.

Site	Lithostratigraphic Unit (LU)	Micromorphology sample	Microstratigraphic Unit (MU)
Schafstall II	GH 1	-	-
	GH 2	SSII-16-1	SS 6
	GH 2a	SSII-17-7	SS5
	GH 2b	SSII-17-1 SSII-17-5	SS4
	GH 2c	SSII-17-1 SSII-17-2 SSII-17-5	SS4
	GH 3	SSII-17-5	SS4
	Hf	SSII-17-6	SS4
	GH 4	SSII-17-9	SS3
	GH 5	SSII-17-10	SS3
		SSII-17-4 (Upper)	SS2
	GH 6	SSII-17-4 (Lower) SSII-17-12	SS1
Fetzershaldenhöhle	GH 1	FH-13-1	FH4
	GH 2	FH-14-1	FH3
	GH 3	FH-13-2	FH2
		FH-13-3	FH1
Lindenhöhle	GH 1	-	-
	GH 2	LH-13-3	LH4
	GH 3	LH-13-2 (upper)	LH3
		LH-13-2 (lower)	LH2
	GH 4	LH-3-1	LH1

Table 2. Summary table for correlating cave sites, lithostratigraphic units (LUs), micromorphology samples and microstratigraphic units (MUs) for Fetzershaldenhöhle, Lindenhöhle, and Schafstall II. Adapted from **Paper III**.

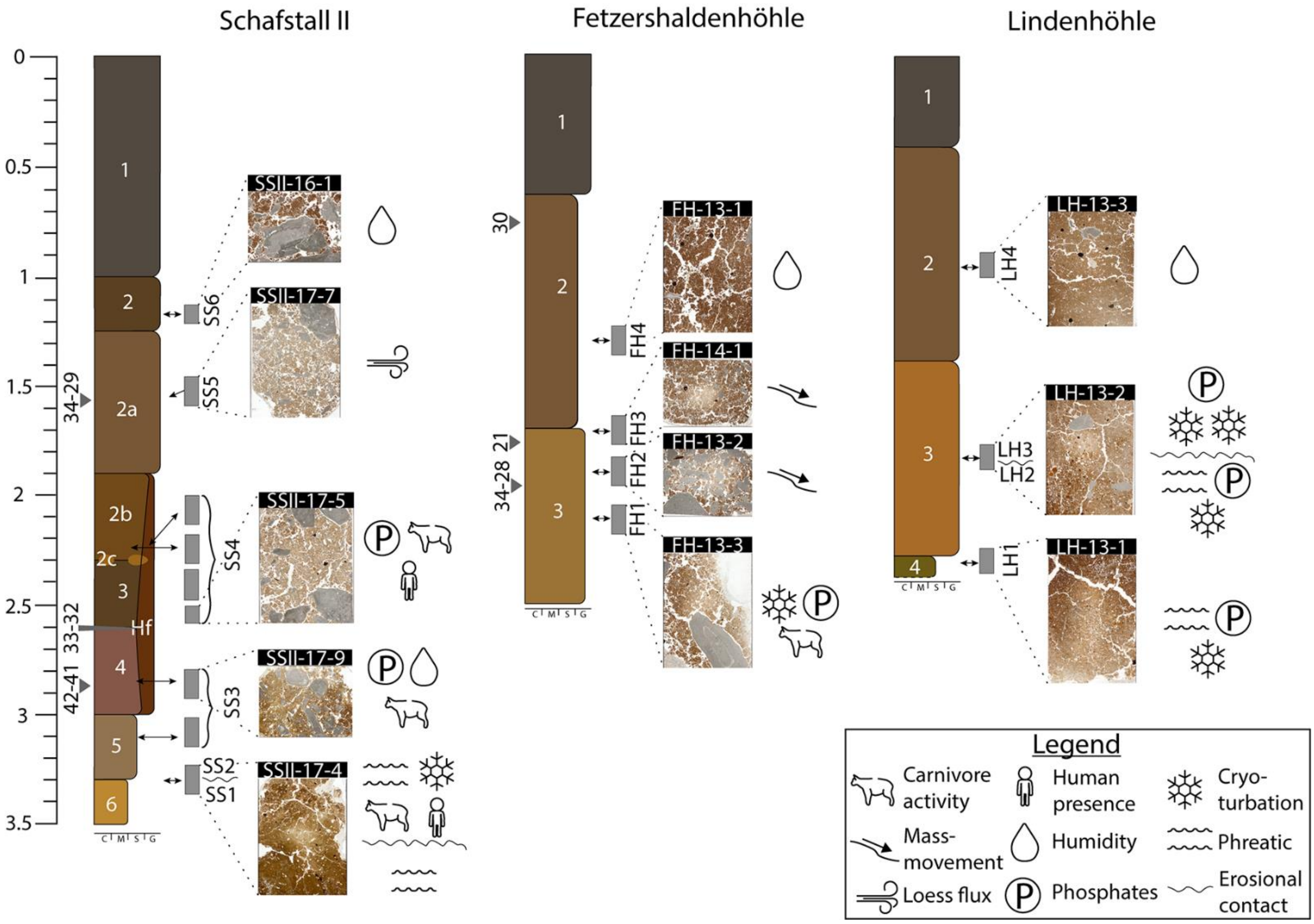

Figure 15. Summary stratigraphic logs of the excavated sequences from Scafstall II, Fetzershaldenhöhle and Lindenhöhle. To the right of each log location of micromorphology samples followed by MU classification and main microstratigraphic features. To the left of the logs from Schafstall II and Fetzershaldenhöhle C14 dates in Kcal BP. Used from **Paper III**.

5. Discussion and Conclusions

5.1. Regional formation processes and settlement patterns in Kazakhstan

This thesis demonstrated that even though karst/pseudokarst, loess and spring settings are prominent contexts for archaeological investigation in the IAMC, they each have a unique set of attributes that influences their archaeological potential. Here, I discuss the main biases inherent to each geomorphic context regarding the preservation of Pleistocene sediments and the discovery of new archaeological sites.

Loess thickness is a crucial limiting factor for discovering new open-air sites in the IAMC and may explain the absence of Middle Palaeolithic stratified sites in Kazakhstan (Fitzsimmons et al., 2017). In this context, the cover of extensive landscape areas with loess introduces biases in the assessment of the archaeological record. First, the difficulty in accessing older sites distorts any assessment of diachronic site distribution. Second, because loess sites can only be found by surveying exposed sections like riverbanks, this creates a skewed image of landscape preference and site selection. In this context, the archaeological visibility of loess sites might be greatly influenced by the intensity of surface erosion. The number of Palaeolithic sites found in loess is much higher in heavily dissected loess sequences, like the Chinese loess plateau, where Early Palaeolithic loess sites have also been found (Sun et al., 2012; Nian et al., 2016; Zhu et al., 2018). In contrast, loess sites in the Central Asian piedmonts have a low discovery potential, but, when found, are multi-layered demonstrating repeated hominin occupations (Fitzsimmons et al., 2017).

In comparison to loess, spring sites have a high discovery potential since they are often formed by tectonic activity and can be easily targeted by satellite imagery and field survey, because they differ greatly from the surrounding steppe vegetation. However, discharge mechanisms in springs vary (Springer & Stevens, 2009) and it is possible that some springs have formed during the Holocene, while others may cut through older Pleistocene deposits, such as the case of the site of Ushbulaq (Anoikin et al., 2019). In this regard, even though we found spring sites in each of our four study regions, their mixed surface lithic assemblages suggest various formation processes, with some related directly to springs as habitation sites and others probably originating from the exposure of buried archaeological remains. Stability of spring recharge (Cartwright & Johnson, 2018) is a prospective parameter for narrowing down spring sites of higher archaeological interest, as it could be modelled to distinguish between ephemeral and perennial springs. In contrast to ephemeral springs, springs with perennial freshwater discharge would be significant landmarks for hominins during the climatic fluctuations of the Late Pleistocene and more frequent visits to these localities would result in a higher accumulation of cultural material. Even though the systematic targeting, survey and modelling of springs lie outside the scopes of this study, the discovery of new spring sites in Kazakhstan (Anoikin et al., 2019; Kunitake & Taimagambetov, 2021) corroborates our hypotheses and highlights the importance of these geomorphological context for future archaeological work in Kazakhstan and Central Asia.

Since the effort to locate Pleistocene sediments in caves and rockshelters in Kazakhstan has yielded mixed results, I have demonstrated that structural factors, environmental context and regional sediment sources influence the preservation potential and visibility of archaeological assemblages found in caves. Structural instability is a particularly important factor since it can seal archaeological levels from erosion, lead to the discovery of hidden caves by extensive collapse, modify the available living space and provide pathways for the input of surface sediments. In this regard, the importance of tectonic structures for cave evolution in tectonically active regions like Kazakhstan would suggest the need for changing survey strategies for discovering new caves, by targeting areas where mapped faults intersect the landscape. Nevertheless, the formation history of cave sites in Kazakhstan is also influenced by the regional semi-arid environment, as demonstrated by the combined analysis of sediment micromorphology and field data in the Qaratau mountains. Loess-like sediments dominate the depositional sequences found in caves and rockshelters, with aeolian loess being one of the main sedimentary components. However, the variability in the distribution of aeolian loess in the Kazakh piedmonts (Li et al., 2015, 2020) and the frequently observed erosional processes associated with the exterior of caves, could potentially explain the high frequency of empty caves in Kazakhstan. Autochthonous sediments have a more limited distribution and are associated with reworked karstic sediments and roof spall originating from thermostatic weathering (Cremaschi et al., 2015). In pseudokarst features parent lithology influences greatly the probability of sediment accumulation and, therefore, archaeological preservation. Overall, sediments originating within the caves mix with the aeolian component by colluvial and mass-movement processes triggered inside the cave environment, which implies that erosional processes occurred in the interior of specific sites. The overlapping of aeolian and colluvial processes seems to be a recurring pattern in both the semi-arid Central Asia and the more humid Altai region (Strasnaya cave; Krivoshapkin et al., 2018, 2019; Chagyrskaya cave; Derevianko et al., 2018; Ust'-Kanskaya cave; Lesage et al., 2020), however an important distinction exists. Specifically, cave sediments in the humid Altai seem to record more intense deformation processes attributed to freeze-thaw (Morley, 2017; Derevianko et al., 2018; Krivoshapkin et al., 2019), which could lead to mixing of the archaeological remains but not erosion of cave deposits. In contrast, the semi-arid caves in Kazakhstan record more intense gravitational processes that seem to promote the erosion of cave deposits and cave sites.

5.2. Local formation processes and settlement patterns in the Swabian Jura

This thesis demonstrated that despite differences in chronology and context, comparable formation processes characterize the low-density sites of Fetzershaldenhöhle, Schafstall II and the entirely geogenic site of Lindenhöhle, in the Swabian Jura. Even though my analysis provided a plethora of novel information regarding the stratigraphy, chronology and palaeoenvironmental context of the investigated sites and valleys (see **Paper III**), here I discuss only the implications that the identified processes have for site integrity and settlements patterns.

Schafstall II is of special interest in this regard, since previous research by Toniato, (2020) identified potential differences in site use as a result of geogenic or anthropogenic processes, but did not provide a conclusive interpretation. The freeze-thaw processes that I identified in Schastall II could have reworked partially specific deposits but were not major enough to change dramatically the archaeological sequence. These findings suggest that the differences in site use identified by Toniato (2020) are most probably related to hominin choices and not post-depositional reworking by geogenic processes. Moreover, I demonstrated that animal activity including carnivore denning has a major depositional effect in both Schafstall II and Fetzershaldenhöhle.

In general, I argue that three key points characterize the low-density record of Schafstall II and Fetzershaldenhöhle:

1) The lack of anthropogenic features and anthropogenic sediments even on the microscale, which in the case of the Swabian Jura range from combustion by-products to various site maintenance activities, including dumping, sweeping and trampling (Schiegl et al., 2003; Goldberg et al., 2003; Miller, 2015).

2) The rare occurrence of certain geogenic processes that seem to have rendered the sites uninhabitable during specific intervals. The first process is associated with the karstic conditions that characterize the basal unit in Schafstall II (GH 6), and the second process is associated with the roof collapse event that was documented in the upper part of GH 3 in Fetzershaldenhöhle.

3) The increased presence of fauna and carnivores.

In this context, I demonstrated an interesting interplay between hominins and animals in the formation of these low-density sites, as suggested by the major presence of biogenic materials related to animal/carnivore activity and few hominin artifacts. Since these biogenic and anthropogenic materials were not mixed by geogenic processes, I suggest that their concurrent presence in the investigated deposits results from the superimposition of hominin occupation and animal/carnivore denning horizons. Similar interpretations associating low-density Palaeolithic sites with the formation of palimpsests by hominin-animal activities have been suggested for carnivore dens in various other contexts (Villa & Soressi, 2000; Morley, 2017; Sanchis et al., 2019). However, in the case of the Swabian Jura, the antagonistic relationship between carnivores and hominins over caves appears to be particularly important for hominin settlement patterns and the formation of dense occupation horizons. Hyenas and cave bear dens are more numerous during the Middle Palaeolithic (see section 1.3.2.), while the increased human presence in the Upper Palaeolithic probably contributed to the decline and local extinction of cave bears by the LGM (Münzel et al., 2011). Overall, the increased human presence over the Swabian Palaeolithic is associated with a decrease in the amount of faunal material accumulated in the caves by carnivores (Conard, 2011; Camarós et al., 2016), demonstrating that the role of carnivores as depositional agents is influenced by the settlement patterns of the Palaeolithic groups. Furthermore, the major biogenic component in the deposits is associated with the remains of animal activity and most often carnivore coprolites.

Hominins occupied the low-density sites of Schafstall II and Fetzershaldenhöhle, sparsely for task-specific activities, with some evidence suggesting that Schafstall II was used as a short-term hunting camp (Toniato, upcoming paper). The sparse hominin site use during the Upper Palaeolithic facilitated the frequent use of the same cave by animals/carnivores, leading to the deposition of high amounts of biogenic material that played an important part in the accumulation of thick stratigraphic sequences in all the investigated sites. In contrast to this low-density record, many Swabian caves seem to document multiple instances of long-term residential use, even though their stratigraphies are as well punctuated by levels of lower find density or occupation hiatuses (Conard & Bolus, 2006, 2008; Conard et al., 2012).

5.3. Concluding remarks

This cumulative PhD thesis investigated the effect of formation processes on the formation and distribution of Palaeolithic sites, based on a regional scale analysis in Kazakhstan, Central Asia, (*Project 1*) and a more local scale analysis in the Swabian Jura, Germany, (*Project 2*). Project 1 suggested that specific geomorphic contexts (springs, loess, caves and rockshelters) are more probable to preserve Palaeolithic sites in Kazakhstan and that the unique formation history of each geomorphic context determines the type of extractable archaeological data. In this regard, the analysis of caves and rockshelters in the Qaratau mountains demonstrated that the distribution of cave sites in Central Asia might be closely associated with formation processes triggered by the regional semi-arid environment. Project 2 focused on the largely geogenic sequences of Schafstall II, Fetzershaldenhöhle and Lindenhöhle, demonstrating that the formation of low-density sites in the Swabian jura is associated with animal activity, lack of reworking processes and absence of anthropogenic materials even in the microscale.

The conclusions of these projects highlighted that diverse formation processes might lead to the same end-result, sites with low find-densities. In the context of Central Asia, my study suggests that the uneven distribution of sites between the poorly occupied Kazakhstan and the richly occupied Altai might also reflect variations in the geogenic processes that govern the formation of cave sediments and the stability of cave environments. In short, the lack of multiple sediment sources and the intense erosion that characterizes the semi-arid regions of Central Asia might be translated to a lower density of Palaeolithic sites. Moreover, even though ecological models suggest that Central Asian piedmonts served as refugia fostering hominin occupation, the archaeological reflection of these models is still extremely blurry. In this regard, my study demonstrates that in case hominins roamed the Kazakh piedmonts, other geomorphic contexts, such as loess and springs, might be more promising than caves and rockshelters in preserving archaeological sites.

If Kazakhstan presents an archaeological picture of few Palaeolithic sites in an overall poorly occupied record, the Swabian Jura provide the opposite picture; a rich occupation record with few poorly occupied sites. In contrast to Kazakhstan, my study in the Swabian Jura demonstrated that the low find density in Schafstall II and Fetzershaldenhöhle cannot be explained by geogenic processes that could erode the accumulated sediments. In this regard, we could safely assume that the presence of human artifacts in those caves and rockshelters is directly related to human choice. Fetzershaldenhöhle and especially Schafstall II were most probably used for short-term logistical activities, such as hunting stops (Toniato, upcoming paper) while the sterile sequence in Lindenhöhle demonstrates that some caves were not occupied at all. I suggest that these sites were used ephemerally for short-term logistical activities by the hominin groups that occupied the valleys of the Swabian Jura. In the absence of major hominin occupation, the thick depositional sequences found in these caves were also formed by increased animal activity, including carnivore denning.

From a methodological standpoint, my thesis addressed inherent biases in the archaeological record, by targeting low find density contexts in different scales of analysis. Understanding the interplay between the natural and anthropogenic processes that form low-density sites, in particular, is a critical step before addressing questions of settlement dynamics. In this regard, I propose a research strategy that combines site formation processes and distributional analyses, as outlined in **Paper I** and **Paper II**, for exploring the completeness of the archaeological record and for investigating site use on a regional scale. This methodology is based on the use of field survey to assess statistically the distribution of archaeological sites over a given area and on the excavation of test-pits for the procurement of high-resolution data to elucidate the formation history of individual sites. By following this approach, this thesis addressed qualitative research questions regarding inter-site variability and site formation processes, which often remain unaddressed by survey projects treating the distribution of sites on the landscape purely as data points. In this context, in **Paper III** I propose that a similar strategy focusing on the regional evaluation of the archaeological record, rather than the investigation of single sites, is necessary to address the inter-site variability that characterizes site use in hunter-gatherer Palaeolithic contexts, such as the Swabian Jura.

6. References

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Papers

Paper I

Iovita, R., **Varis, A.**, Namen, A., Cuthbertson, P., Taimagambetov, Z., & Miller, C. E. (2020). In search of a Paleolithic Silk Road in Kazakhstan. *Quaternary International*, *559*, 119–132. https://doi.org/10.1016/j.quaint.2020.02.023

Paper II

Varis, A., Miller, C., Cuthbertson, P., Namen, A., Taimagambetov, Z., & Iovita, R. (2022). The Effect of Formation Processes on The Frequency of Palaeolithic Cave Sites in Semi-Arid Zones: Insights From Kazakhstan. *Geoarchaeology*. https://doi.org/10.1002/gea.21909

Paper III

Varis, A., Miller, C. E., Toniato, G., Janas, A., & Conard, N. J. (2022). Using formation processes to explore low-density sites and settlement patterns: A case study from Swabian Jura. *Journal of Paleolithic Archaeology*. (submitted)

In search of a Paleolithic Silk Road in Kazakhstan

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Abstract

Paleoanthropological data suggest that the Late Pleistocene was a time of population contact and possibly dispersal in Central Asia. Geographic and paleoclimatic data suggest that a natural corridor through Kazakhstan linked areas to the north and east (Siberia, China) to those further to the west and south (Uzbekistan), much akin to a Paleolithic Silk Road. We review the known Pleistocene archaeology and paleoclimatic setting of this region and provide a geoarchaeological framework for contextualizing preliminary survey results of the PALAEOSILKROAD project's first three seasons of fieldwork. We discuss some systematic biases in three geomorphic and sedimentary archives: karst, loess, and spring deposits, specifying ways in which these biases might determine the kinds of data that are extractable by systematic survey. In particular, we caution about the possibility of future systematic biases in chronology that could come about as a result of the type of geomorphic context in which the sites are recovered. We conclude with recommendations for future work in the area.

Keywords: geoarchaeology, Paleolithic, Central Asia, systematic survey, taphonomy

1. Regional setting: The Silk Road in the Late Pleistocene

The Silk Road was an ancient network of trade routes that constituted the economic, cultural, and biological link between the Middle East and East Asia for at least a millennium during late antiquity and the early Middle Ages. To avoid crossing the deserts and high mountains of arid central Asia – one of the driest regions in the world – travelers used the more temperate corridors through the mountain foothills (piedmonts) (Figure 1). Recent research has shown that the movements of pastoral nomads during the Bronze and Iron Ages also reflected a connectivity of these same pathways through the piedmonts (Frachetti et al., 2017). In this paper, we will argue that at least some of these corridors must have been used by people still earlier, in the Paleolithic (for a similar hypothesis further west on the Silk Road, see Nasab et al., 2013). We will review the current state of knowledge on the Stone Age archaeology of the Kazakh piedmonts, and provide a geoarchaeological context for current and future survey work.

1.1. Central Asia as a crossroads for Paleolithic populations

An explosion of recent paleogenomic research, along with new techniques for identifying fossil human bone fragments from archaeological contexts have given us new data on the timing of modern humans' arrival and colonization of the inner parts of Asia. Moreover, there is now evidence of multiple encounters (for a review, see Gokcumen, 2019) between the (so far) three different metapopulations, the Neanderthals, Denisovans, and modern humans. Where exactly these encounters took place is not clear, but the amount of time spent in chrono-spatial overlap between them is large enough that the entire territory of central Asia is a possibility (see also Boivin et al., 2013).

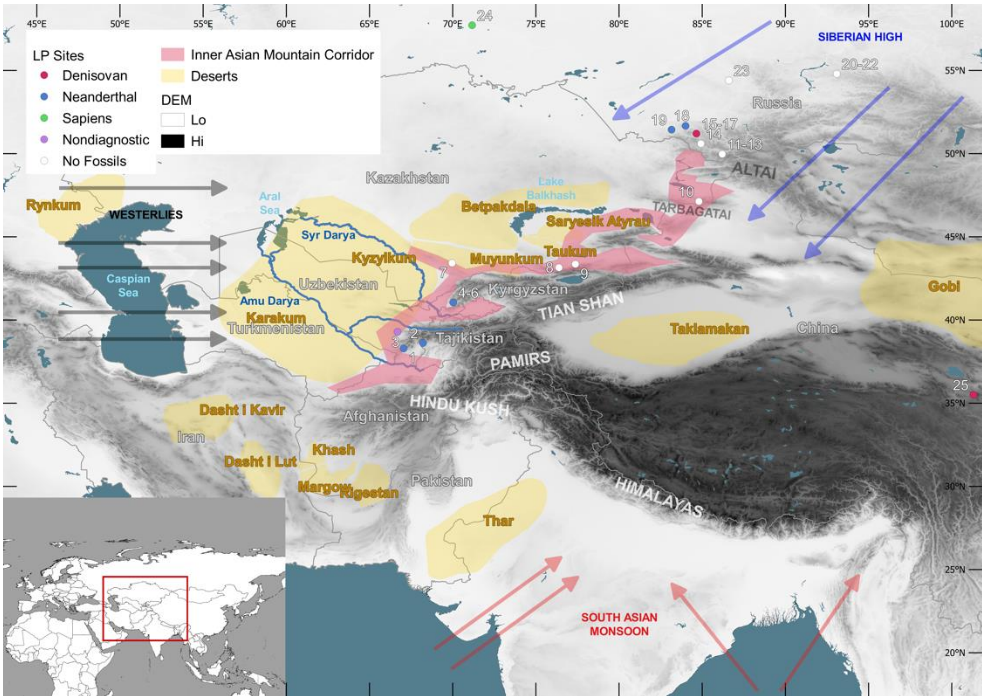

Figure 1 Late Pleistocene sites in and around central Asia, shown in relation to major topography, deserts, and the area of the proposed Inner Asian Mountain Corridor (IAMC). Also shown is the opposition of the Westerlies to the seasonal weather systems of the Siberian High Pressure System and the South-Asian Monsoon. 1) Teshik-Tash, 2) Khudji, 3) Anghilak, 4-6) Kulbulak, Obi Rakhmat, Katta Sai, 7) Valikhanova, 8) Maibulak, 9) Rahat 1, 10) Ushbulaq, 11-13) Malo Yaloman, Kara-Bom, Kara-Tenesh, 14) Ust'-Kan, 15-17) Denisova, Ust-Karakol 1, Anui, 18) Okladnikov Cave, 19) Chagyrskaya, 20-22) Ust'-Maltat 2, Derbina 4 & 5, 23) Mokhovo 2, 24) Ust'-Ishim, 25) Xiahe. Data sources: Global Administrative Areas (GADM) (Hijmans, 2012), vector and raster map data from Natural Earth (naturalearthdata.com) and Shuttle Radar Topography Mission (SRTM) Version 4 (Jarvis et al., 2008).

Likewise, the antiquity of the supposed modern human migrations has been greatly stretched by the new data (Martinón-Torres et al., 2017). A pattern is emerging whereby the earliest modern human fossil dates are furthest east in China (at Daoxian, ca 80 ka, Liu et al., 2015) and the later ones in Siberia (Ust'-Ishim, Fu et al., 2014; Baigara, Kuzmin et al., 2009) and Mongolia (Salkhit, Devièse et al., 2019). A possible explanation for that could be a fast, southern coastal route into Asia (James & Petraglia, 2005; Reyes-Centeno et al., 2014), followed by a slower, 'northern route' through Central Asia (Zwyns et al., 2019). Items of portable art and jewellery appear in the Upper Paleolithic repertoires of sites in southern Siberia and Mongolia (Rybin, 2014; Zwyns et al., 2019) and, combined with some characteristics of the lithic assemblages, have been interpreted by several researchers as documenting the first modern human presence in northeast Asia. There is debate about whether modern humans arrived first in Siberia and Mongolia (and how) and then entered China via the Dzhungar Gate (Derevianko et al., 2012) or if they came north through central Asia and Kazakhstan first. One particular difficulty is posed by the fact that so far, all the fossils discovered in Central Asia are of extinct, archaic humans . This means that any modern humans going north and east must have gone through a territory that was already occupied. The details of these movements remain so far completely unknown, largely due to the comparative lack of systematic, large-scale work in the region connecting Fergana and the Altai via the high mountain chains (Tian Shan and Dzhungarian Alatau)(Fitzsimmons et al., 2017).

It is also worth mentioning that not only modern humans are on the move. The new Denisovan fossil from Tibet (Chen et al., 2019), indicates how little we know about these populations' movements in the earlier part of the record. Given its landscape position, at over 3000 m.a.s.l., the Baishiya Karst Cave find (Xiahe, Tibet) raises questions about the Denisovans' long term occupation of and adaptations to high mountain environments (Huerta-Sánchez et al., 2014) – and likewise points to our sampling biases in terms of survey strategy. In an attempt to make up for the lack of fossils, several researchers have attributed the appearance of 'Levallois'-like stone industries in China at sites such as Jinsitai (F. Li et al., 2018) and Guanyindong (Hu et al., 2019), to Neanderthal migrations, although others disagree on the industrial attribution at Guanyindong (F. Li et al., n.d.; Y. Li et al., 2009).

In order to deal with the dearth of data, several authors have used predictive mathematical models to propose various routes taken by hominins. Li et al (2019) used Least Cost Path models to evaluate the likelihood of various competing routes between known sites in the context of both glacial and interstadial climatic conditions. Their approach is interesting particularly for suggesting corridors through deserts such as the Gobi, which have been previously considered barriers to dispersal (Dennell, 2017). Using estimations of ecological tolerance, in particular of low temperature and high aridity, Beeton and colleagues (2014; Glantz et al., 2015) proposed a model in which populations retreat to the foothills of the Altai and Tian Shan during cold periods and expand into the lowlands during warmer and wetter phases. Although these models move the discussion along, it is necessary to point out that they suffer from the poor quality and density of the input data, as many of the archaeological sites used to generate the models suffer from poor chronostratigraphic controls and the paleoenvironmental data is largely extrapolated from regional or even global models, rather than from locally-derived proxies.

1.2. Physical geography and climate restrict possible pathways

Adapting to climate change in a region like arid central Asia is a major challenge for humans. Its high mountains and extensive deserts already represent significant geographic barriers to dispersal and habitation. These changes would have been more abrupt and would have had a more powerful effect in the Pleistocene. During cold glacial periods, the high latitude ice sheets and intensification of the Siberian high pressure system would have resulted in a southward movement of the polar front (Machalett et al., 2008). This in turn intensified aridity, reducing still further the habitable area for Paleolithic hominins, who, unlike Silk Road merchants, were on foot and depended on hunting and collectible plant resources. In this context, it is the mountains, and the water sources originating there that made life possible for hominins and animals alike. In particular, the piedmonts of the Pamir – Tian Shan – Dzhungar – Altai chain form an unbroken Inner Asian Mountain Corridor (IAMC, sensu Frachetti, 2012), which extends from Afghanistan to Siberia, sandwiched between the high mountains and the desert plains (see Figure 1). The foothills of the IAMC form a continuous landscape featuring complex topographies shaped by tectonics, offering sheltered micro-climates and rich plant and animal resources, as well as ample opportunities for ambush hunting (King & Bailey, 2006). The landscape in the IAMC is also affected by the local growth and retreat of mountain glaciers (Blomdin et al., 2016; Koppes et al., 2008). However, these events are not always correlated with global climate (for a review, see Owen & Dortch, 2014; also Figure 2). In particular, the growth of glaciers in the Pamir and Tian Shan ranges is driven by moisture availability, rather than lower temperatures (Koppes et al., 2008). This contrasts with the Altai, where temperature is the primary driver (Lehmkuhl et al., 2011). This means that glacier growth, which necessarily would have restricted movement in the high mountains of Central Asia by sealing up mountain passes, does not correlate well with global cold phases.

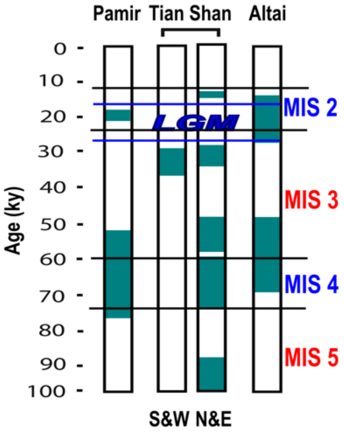

Figure 2 Maximal extent of mountain glaciers in the IAMC (data from Owen and Dortch (2014)). Marine Isotope Stages (MIS) and the Last Glacial Maximum (LGM) shown for context (red = warm (interstadial), blue = cold (stadial)).

1.3. Known Paleolithic contexts

As mentioned before, the archaeological data from the Pleistocene IAMC data are scarce. Part of the reason why lies with the history of systematic research. The first finds of individual stone tools can be traced back to the 1850s, when locals found several arrowheads during the excavation of a kurgan in Southern Kazakhstan, and blades were also found on the Mangyshlak Peninsula (Caspian) in 1862 (Chekha, 2017). Similar findings were recorded by Russian geologists in eastern Kazakhstan, where a museum of local history was established in 1883 containing approximately 80 stone tools. During the construction of the Turksib (Turkestan-Siberia) railway in 1928, a large Upper Paleolithic-type core was discovered from the pit at a depth of 2 m in a locality of Altyn-Kolat, South Kazakhstan (Kh. Alpysbaev, 1970). Systematic surveys and excavations began in the 1950s, following news of the discoveries made by Okladnikov in Uzbekistan (Ozherelyev, 2007). Khasan Alpysbaev's work concentrated on the South Kazakhstan region, where he discovered abundant surface scatters, as well as a number of cave sites, such as Ushbas and Qaraungir (also known as Karaungur (Zh. Taimagambetov & Nokhrina, 1998)). Alan Medoev undertook surveys mainly in the regions around Mangyshlaq, Saryarga, and Lake Balkhash (Kh. Alpysbaev, 1961; Medoev, 1964). Their work was continued by Zhaken Taimagambetov (e.g., Zh. Taimagambetov, 1983, 1990, 1997; Zh. Taimagambetov & Ozherelyev, 2008, 2009), Olga Artyukhova in the Central and Western regions (Artyukhova, 1990; Artyukhova & Mamirov, 2014), and Valeriy Voloshin in Northern Kazakhstan (Voloshin, 1971), along with many collaborators.

Most of the finds reported as sites (Rus.: ‘*otkrytye mestonahozhdeniya*’) are surface lithic scatters and cannot be directly radiometrically dated. Assemblage attributions to period and cultural entities are almost always based on lithic typology. Some sites, such as those of Semizbugu (Pribalkhash) (Medoev, 1982), Mangyshlaq (Caspian shore) (Derevianko et al., 1999), and Qyzyltau (Muyunqum/Eastern Karatau border) (Derevianko et al., 2002) represent large accumulations of stone tools in deflated contexts. Others, such as the Batpak (Klapchuk, 1971) sites in central Kazakhstan, are from colluvial or other formerly primary stratified contexts. Only a handful of primary context stratified sites have been discovered and studied across the vast area from the Irtysh to the Karatau range near Shymkent. They can be found in different geomorphic and geological contexts such as loess, river terraces, and in spring deposits (travertine). The earliest sites, of the Qoshqorgan-Shoqtas complex, formerly known as Koshkurgan-Shoktas (Derevianko et al., 2000) are found in travertines in South Kazakhstan. In loess, there are the Upper Paleolithic sites of Valikhanova (H. A. Alpysbaev, 1979; Zh. Taimagambetov, 1990)) and Maibulaq (Zh. Taimagambetov, 2009; Zh. Taimagambetov & Ozherelyev, 2008), recently reviewed and re-dated by Fitzsimmons et al. (2017) to the period between roughly 40 and 25 ka. The site of Rahat was discovered in the last decade and excavated only in the past several seasons (Ozherelyev et al., 2019), with an OSL chronology pending. In the East Kazakhstan region, only two stratified Upper Paleolithic sites are known, Shul’binka on the Irtysh (Z. K. Taimagambetov, 2012; Zh. Taimagambetov, 1983), and the recently discovered site of Ushbulaq, on the bank of a spring in the Shilikti Valley near Lake Zaisan (Derevianko et al., 2017). The latter is radiocarbon-dated to 45 249 – 44 012 calBP (Anoikin et al., 2017). Finally, in caves, only one verifiable Pleistocene context is known, from Ushbas in the South Kazakhstan region (recently reexcavated by Grigoriev & Volkov, 1998), which featured a small collection attributed typologically to the Upper Paleolithic.

2. Possible archaeological contexts

For the preservation and discovery of Paleolithic sites, both deposition (leading to preservation) and exposure (leading to higher visibility) are required. Given the general landscape characteristics and enormity of the landmass of Kazakhstan, this presents a series of unusual challenges. Nevertheless, several patterns emerge: caves and loess present good, if incomplete, archives of past behavior, and spring and river terrace sites bring a variety of opportunities and problems to the table. In our survey, terraces of large rivers have been the least promising of these contexts, so we will limit our discussion to karst, loess, and springs.

2.1. Karst and pseudokarst

Caves tend to be a major focus of any archaeological survey strategy, as they generally form good sediment traps corresponding to relatively long time periods and are thus well-suited to sequence-building. Unfortunately, the general characteristics of karst in Kazakhstan are poorly known even when compared with other Central Asian former Soviet republics. Here we focus on specific examples in order to outline some basic geomorphological characteristics of the karst and pseudokarst found in the IAMC of Kazakhstan and evaluate its potential for preserving Pleistocene archaeology. Such an evaluation is crucial for beginning to apply more sophisticaled predictive models of cave site location (for an example of such models, see Heydari, 2007; Märker & Heydari-Guran, 2009).

2.1.1. Solutional caves

Dissolution of carbonate rocks by circulating meteoric water is the most frequent mechanism for the development of karst landscapes and the formation of solutional caves (Audra & Palmer, 2011). More specifically, the majority of caves are formed by surface flowing water that absorbs carbon dioxide from the atmosphere and the soil, acquiring thus the necessary solution capacity to react chemically with the carbonate bedrock and to form underground conduits. Based on the level of the water table, caves form either in the unsaturated portion of the subsurface (vadose zone) or in the saturated aquifers (phreatic zone). Vertical fluctuations of the water table induced by changes in the base level, result in the development of extensive cave systems that form complex morphological patterns (Palmer, 1991).

In Kazakhstan, the presence of extensive cave systems in a single hydrological catchment seems to be relatively infrequent. In that sense, the occurrence of isolated or single chamber caves that seem to have no genetic relationship to the modern topography (sensu Frumkin & Fischhendler, 2005) are common. In general, the average size of the surveyed caves is small, since they usually represent the enlargement of a single conduit without the development of a network of passageways and chambers. The majority of the surveyed caves are in the later stages of karst evolution and they are characterized by drained passages, wall and ceiling collapse, as well as dissection by surface erosion (Palmer, 2003). Water flow in modern cave passages was encountered only in a few instances, and speleothem formation was also limited. The few speleothems recorded include tiny globular corallite structures known as ‘popcorn’ and formed under the evaporitic conditions of cave entrances (Ford & Williams, 2007, p. 281; Self & Hill, 2003) and flowstone deposited on cave floors. A few instances of poorly developed stalactites and stalagmites were also recorded. The lack of suitable speleothems for paleoenvironmental and paleoclimatic reconstructions effectively means that the sedimentary sequence preserved in some features constitutes the only cave archive for these types of analyses (W. White, 2007).

Structural factors seem to play an important role in cave evolution in Kazakhstan. Occasionally, angular walls with straight faces that form triangular entrances and run partially or throughout the depth of the cavities indicate the presence of fault-guided cave development (see Figure 3a). Tectonic stress can also result in plastic (ductile) deformation of rocks, which will eventually lead to the creation of folded but not necessarily displaced strata. This can be seen occasionally via the presence of localized tectonic breccia adjacent to the cave entrance, as in the example shown below (see Figure 3b).

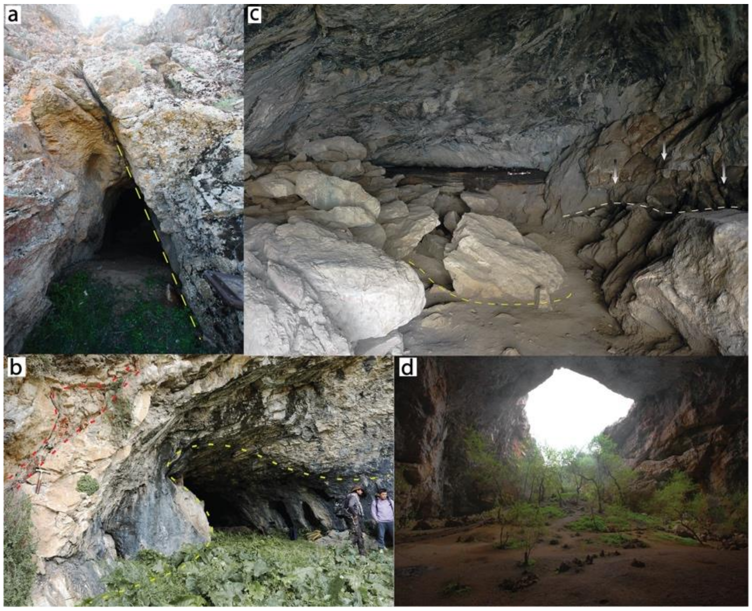

Figure 3 Structural mechanisms affecting cave morphology. A) Ushbas. Yellow dotted line indicates the fault plane parallel to the south wall; slickensides exposed at the face of the fault plane, although not visible from this view, are indicative of vertical displacement (dip-slip fault). B) Marsel. Yellow dotted line, humans for scale; steeply inclined asymmetrical fold acting as the incipient horizon of cave development. Red dotted line, geological hammer for scale; localized matrix-supported tectonic breccia composed of angular carbonate fragments constitutes additional evidence of ductile stress deformation. C) Tuttybulaq 1. White arrows indicate direction of slumping; white dotted line indicates accumulation of slumped material. Yellow dotted lines indicate major fallen boulders associated with ceiling collapse that cover the middle part of the chamber. Scale in the back of the cave is 1 meter. D) Aqmeshit cave. View towards the collapsed dome at the top part of the cave and the accumulated sediment cone below.

On the other hand, more localized and irregular micro-faulting, most probably associated with secondary earthquake activity, has also led to the subsequent dislocation of rocks from the walls and ceilings of some caves resulting in a change of the available cave space. Structurally-induced changes at the approximately 25-meter long main chamber of Tuttybulaq 1 (Figure 3c) provide a prime example of this process. Here vertical dislocation of parts of the southeast wall, indicated by local slumping and accumulation of massive boulders promoted extensive ceiling collapse. This resulted in the vertical expansion of the main chamber on the one hand, and the sealing of Holocene occupation levels (Baytanaev et al., 2017, 2018) by boulder-sized blocks on the other.

Breakdown is a general characteristic of drained caves because the roof of the passages and chambers loses the hydrostatic support of water (Gillieson, 1996, p. 8). Furthermore, long term stress may lead to the progressive collapse of the cave ceiling resulting in domed caves. The dome is defined as “a large hemispheroidal hollow in the roof of a cave formed by breakdown, which prevents bedding and joints dominating the form” (U. S. EPA, 2002, p. 63). In places where a wide roof span is combined with little rock cover, the collapsed dome gets exposed to the surface revealing the underground cavity (Benson & Yuhr, 2016, p. 80). This probably explains the morphology of Aqmeshit cave, a famous religious cave site located in the Baidibek district of Turkestan region (Figure 3D). The cave is more than 150 m long, around 30 m tall and it can only be accessed by a vertical staircase positioned at the highest part of the former ceiling. Following the roof collapse, wind-blown sediment started settling into the exposed chamber building up a sediment cone directly under the dome. Given the possibility of rapid wind-blown sedimentation, it is hard to estimate a minimum age for the collapse of the dome without further survey and analysis. However, the absence of fallen roof rock on the surface and the thickness of the sediment cover indicate that preservation of Pleistocene sediments is possible.

The relationship between tectonics and cave formation observed in the field is confirmed by the pattern of cave location relative to fault lines. For example, in the area of the Lesser Boraldai in the Southern Karatau (Figure 4), a complex of faults intersects the Devonian and early Carboniferous sedimentary rocks resulting in a high relief topography. High escarpments and cliffs feed steep-gradient streams that create deep canyons and ultimately flow into an elongated drainage basin towards the east. At the middle of the basin, the Lesser Boraldai group is formed on the uplifted Devonian complex, with the majority of the cavities mapped directly on the fault line. The Lesser Boraldai group is composed of caves and rockshelters formed on breccia and limestone, with the majority of the features characterized by extensive wall/roof collapse and an absence of accumulated fine sediment. Further to the west, Tuttybulaq 1 (see discussion above and Figure 3C) and 2 are formed in brecciated limestone also intersected by the faults.

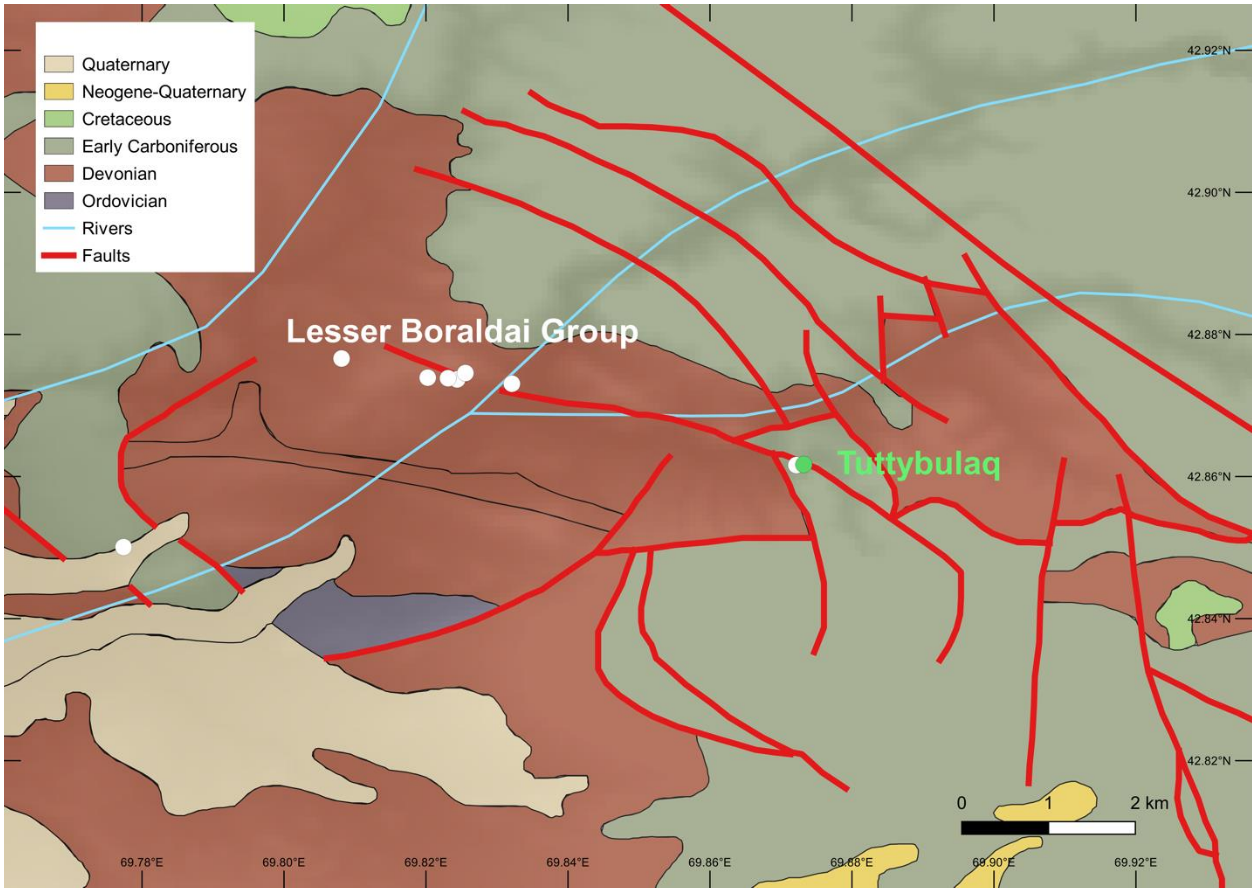

Figure 4 Geology, faults, and rivers surrounding the Lesser Boraldai Group and the Tuttybulaq locality. Data sources: HydroSHEDS (Lehner et al., 2006).; Mineral Deposits Database and Thematic Maps of Central Asia, (Seltmann et al., 2014).

2.1.2. *Pseudokarst and non-karstic processes*

Pseudokarst is defined as any landform that resembles karst, but it has formed by non-solutional processes (Grimes, 1975). From the various types of pseudokarst that have been documented in different parts of the world (Holler, 2019), small sink holes, gullies and loess cavities formed along slopes constitute the most common feature encountered during our survey in Kazakhstan. Karst-like loess features are attributed to piping erosion, viz. the horizontal or vertical removal of soil or unconsolidated material by concentrated water flow (Halliday, 2007, p. 106). They develop under the impact of steep topography, concave slope morphology and intense precipitation (Bíl & Kubecek, 2012; Verachtert et al., 2010). Based on our observations, loess pseudokarst frequently acted as a death trap for modern animals that were fallen in the sink holes or were buried under partially collapsed cavities. This phenomenon implies that the aforementioned features can act as a context for the possible accumulation of archaeological material. However, in contrast to the relatively stable karst caves and rockshelters, loess is highly erodible and susceptible to slumping and other mass movement processes and are thus very dangerous for researchers (Y. Li et al., 2018). In this regard, well-developed loess pseudokarst structures are ephemeral (Lukić et al., 2009; Pavuza & Plan, 2013) and therefore constitute unfavorable features for the preservation of archaeological remains in the long-term.

Pseudokarst can also form by lateral fluvial erosion along the course of rivers and streams. It usually develops as a rockshelter or shallow cave morphology in any type of rock, following zones of weakness induced by tectonics or lithological variation. Parent rock type and the external geomorphic regime influence the accumulation and preservation of sediment in these features. For example, Nazugum rockshelter (Ketmen range of the Trans-Ili Alatau) was initially formed by the lateral eroding action of the Ketmen river system that shaped the intensely dissected volcanic rock highlands. It is located at the foot of a straight cliff not much higher than the current river channel (Figure 5A). Isolated sediment columns that reach up to the ceiling of the rockshelter partially preserve at some places under the brow, revealing that the rockshelter was at some point almost completely filled. However, in the majority of the rockshelter area and especially towards the back of the chamber, sediment cover is absolutely absent and the bedrock is exposed. At the lower part of the stratigraphic sequence, imbricated gravel layers interlaminated with clays and fine sands indicate a period of fluvial deposition and channel widening. This phase was followed by progressive downcutting of the stream's bed and concurrent wind-blown sedimentation in the cavity, as demonstrated by the massive loess deposits that overlie the fluvial layers. The pseudokarstic processes that lead to the active erosion of the sediments are evident by clear morphological features like sediment arches that denote the presence of water channels. These channels flow from the inside of the rockshelter towards the outside and should be attributed to secondary solutional pathways in the parent rock.

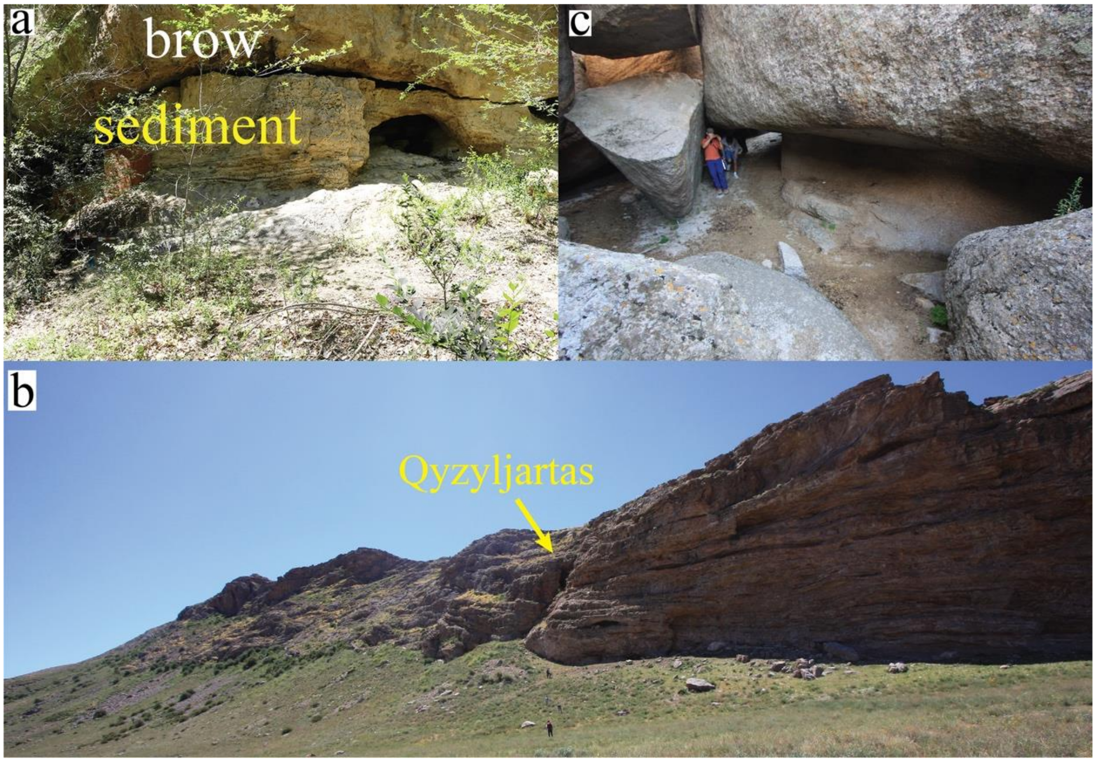

Figure 5. Pseudokarst features and non-karstic processes. A) Nazugum rockshelter. View towards the southern part of the rockshelter where most of the sediment is still preserved. Sediment thickness ca. 2.6 m. Note the sediment arch on the right of the picture indicating active erosion. B) Qyzyljartas. General view of the cave entrance and the adjacent landscape. Note small cavities at multiple points in the outcrop produced by solutional or even aeolian erosion of weak sandstone beds. People for scale. C) Black cave. Curved erosional features produced by stream channels (right side) and mechanical breakdown piling-up boulder-sized clasts (left side). People for scale.

Pseudokarst fluvial features also occur in sandstone, granite and conglomerate. In the absence of allochthonous sedimentation, such as wind-blown loess, the type of parent material, as well as the way it disintegrates and accumulates through time, constitute the dominant factors controlling deposition in the cavity. From the above bedrock categories, only those in sandstone were substantially covered by autochthonous geogenic sediments. These fine-grained sediments accumulate rapidly as a result of in situ chemical and mechanical weathering of sandstone. One example of non-karstic processes shaping sandstone features is documented at the cave of Qyzyljartas that lies on the north-eastern side of the Qaratau mountain range. It is situated almost at the top of a medium-bedded sandstone outcrop, which forms a very steep cliff and overlooks an extensive valley filled with loess and dissected by a more recent river (Figure 5B).The cave itself is infilled by a homogeneous sequence of red silty sands, which is interrupted by allochthonous water-lain deposits that in some cases sort out, reshape and redistribute older sediments, leaving behind well-sorted and rounded quartz grains as well as sandstone rip-up clasts. The fluvial deposits are relatively thick and heterogeneous indicating multiple phases of channelized water flow. These sediments should be associated with an older catchment of the valley river system, even though it is currently unclear if they constitute remnants of actual fluvial action at a higher elevation than the modern valley floor. Nevertheless, the presence of water-lain sediments in Qyzyljartas provides an insight into the diverse erosional dynamics that led to the enlargement of the original cavity and could be potentially attributed to a different climatic and drainage regime in the basin.

On the other hand, Black Cave (Kaz. *Qaraungir* near Taldyqorgan, written here in English translation to distinguish it from the Neolithic site of Qaraungir/Karaungur in the Karatau) is a granitic grotto formed by erosive river action and by the slipping of the giant granite boulders that accumulate as a talus of irregular morphology (Figure 5C). Rock art of most probably Bronze Age on the walls demonstrates human presence and use of space in the feature. However, in comparison with the sandstone example above (Qyzyljartas), Black cave and other granite rockshelters that we recorded are less likely to disintegrate that easily into loose sediment, such as grus (Kajdas et al., 2017), and as a result less probable to accumulate thick autochthonous deposits. Since the rate of surface erosion cannot be surpassed by the rate of geogenic deposition, any artifacts or features deposited in the grotto are less likely to be captured and preserved.

To conclude, locating pseudokarstic features is a challenging task since their occurrence cannot be predicted by a model that is based solely on bedrock classification. However, considering river action as a geomorphological modelling agent, the discovery of these water-cut features may be facilitated from the targeted survey of deep incised canyons and valleys that are not covered by loess.

2.2. Loess

Loess is aeolian fine-grained silt that blankets much of the Central Asian piedmonts (see Figure 6). Alternating loess-paleosol (LP) sequences showcase climatic changes from relatively dry and cold periods (represented by the loess) and relatively humid and warm periods (represented by soil formation). Recent research in Kazakhstan has shown that this information can be combined with that drawn from human occupations to create a relatively nuanced picture of human-environment interactions (Feng et al., 2011; Fitzsimmons et al., 2017, 2018; Machalett et al., 2008; Sprafke et al., 2018). Moreover, sites appear to often be located in similar landscape locations, often at the beginning of alluvial fans created by intramontane rivers.

So far, Paleolithic sites preserved in loess deposits in Kazakhstan are all multi-layered and belong to the same time period, the Upper Paleolithic. The multi-layered aspect of sites such as Valikhanova (Zh. Taimagambetov, 1990), Maibulak (Zh. Taimagambetov & Ozherelyev, 2008), and Rahat (Ozherelyev et al., 2019) is somewhat unusual in the general context of Eurasian Paleolithic sites, where open-air sites often document ephemeral occupations of a particular landscape location. Unlike caves, these open-air locations may reflect unknown and unknowable pragmatic considerations on the part of the ancient inhabitants, some of which may include the presence of trees, proximity to a comparatively sheltered location, or good visibility for stalking animals. In any case, the timing and intensity of occupation should provide a good proxy for occupation patterns during particular time slices.

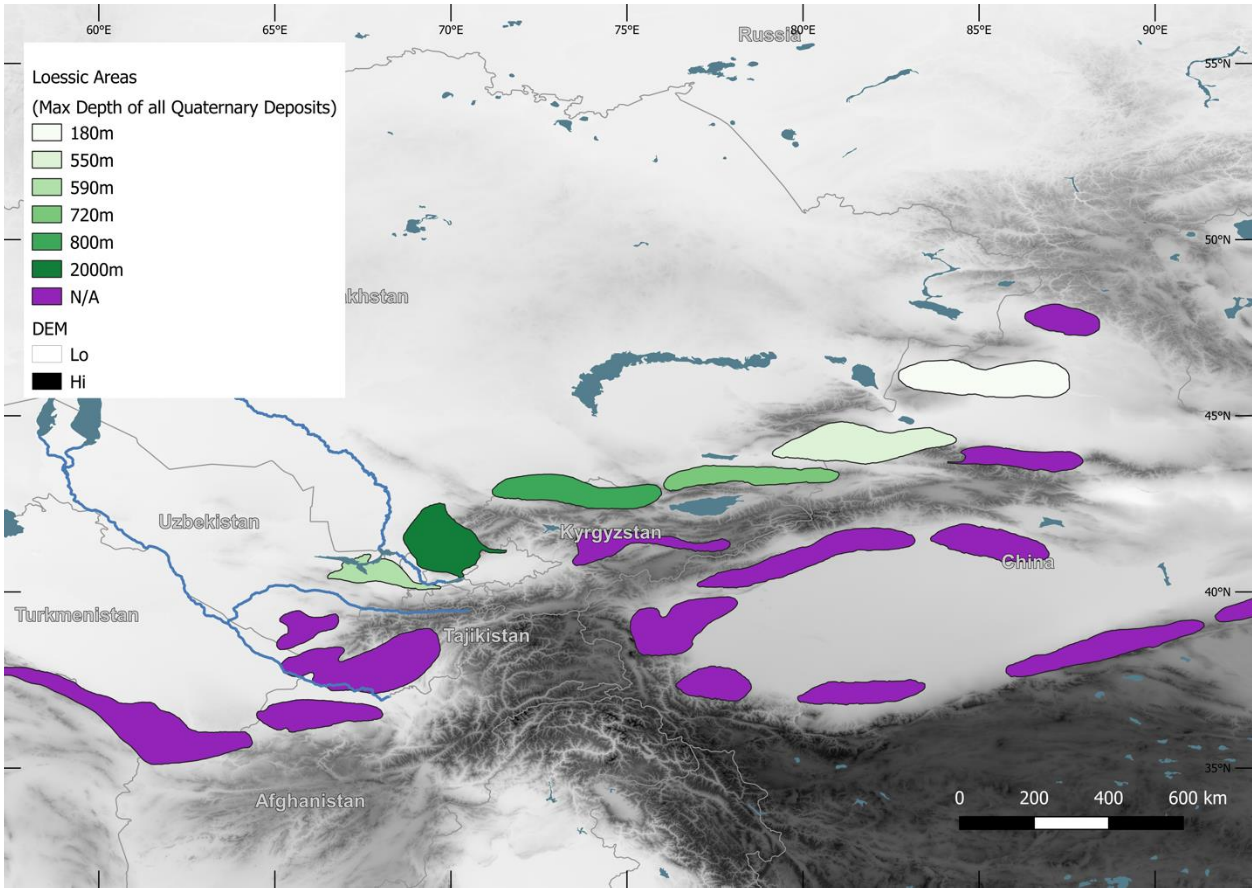

Figure 6. Distribution of loess in Central Asia, after Dodonov (2007). Color denotes maximum thickness of Quaternary deposits in each of the PALAEOSILKROAD study areas. Thickness data are obtained from Soviet geological maps (1:200k). Including data from: Global Administrative Areas (GADM) (Hijmans, 2012) http://www.gadm.org/about, Natural Earth @ naturalearthdata.com, and Shuttle Radar Topography Mission (SRTM) Version 4 (Jarvis et al., 2008) http://srtm.csi.cgiar.org.

2.3. Springs

Springs appear at points in the landscape where groundwater intersects with the topography and flows onto the surface. They emerge in various geological and geomorphological settings under the force of gravity and can be classified in numerous types according to their genetic characteristics (Kresic & Stevanović, 2010, Chapter 2). They constitute locations of significant ecological contribution since they provide freshwater for animals and humans. Furthermore, in semi-arid areas like Kazakhstan where annual precipitation is low, seasonal or perennial springs provide places of hydrologic refugia during periods of fluctuating climate (Cartwright & Johnson, 2018). The potential role of springs for hominin survival, evolution, and dispersal has been explored with positive results in the arid environments of East Africa (Cuthbert et al., 2017). In this framework, Barboni et al. (2019, table 1) , catalogue around 50 spring localities and sites associated with Pliocene and Pleistocene paleontological and archaeological remains from Africa to the Middle East.

Previous archaeological research in Southern Kazakhstan documented a handful of open-air sites located in travertine precipitating springs (Derevianko et al., 1998). The sites, which were dated by EPR (electroparamagnetic resonance, a variant of ESR) to ca 500 - 400 ka, are concentrated in an area of approximately 100 km2, in proximity to Koshkurgan/Qoshqorgan village, at the piedmont plain covering the southwest slope of the Karatau Range (Derevianko et al., 1998). The deposition of calcium carbonate by springs constitutes an ideal preservation agent for archaeological horizons by forming travertine crusts over them or by impregnating (cementing) older sediments. Therefore, these processes can lead to the formation of deposits that are less susceptible to erosion by surface agents, and this explains the unique preservation of such ancient remains in a context otherwise devoid of stratified Middle Pleistocene sites. Given that they are not covered by younger sediments, as in the case of the Koshkurgan/Shoktas sites, spring deposits provide visible and relatively stable landscape features. However, the intensity of freshwater carbonate precipitation and accumulation varies among springs. Specifically, it is a function of local geomorphological and environmental factors such as climate, vegetation, soils, topography, bedrock, hydrology and of course time (Andrews, 2006; Mors et al., 2019; Viles & Goudie, 1990). Some springs may deposit carbonates only occasionally (e.g. Smieja & Smieja-Król, 2007) and therefore lack consolidated travertine or tufa deposits. Naturally, this implies that archaeological sites in their vicinity are more exposed to erosion.

The previous discussion highlights springs as a possible target of systematic survey, as they combine obvious resource value to hominins with deposition mechanisms and relatively easy mapping. Moreover, unlike large river valleys, springs are manageable in size and present a better signal-to-noise ratio for spotting artifacts on the surface. No data source is perfect, however, and springs have their drawbacks: for instance, given their fluctuating course, lithics found on the surface at one locality may have been part of a channel that is now extinct, something that can only be checked through coring or test excavations. All in all, however, we predict that springs will eventually provide a good source for finding Paleolithic sites in Kazakhstan.

3. Preliminary findings

In three field seasons from 2017-19, the PALAEOSILKROAD team has conducted around six months of survey, primarily targeting caves and rockshelters, in addition to continuing work at some of the known loess sites (Maibulak and Rahat). Spring sites were surveyed in connection with our karst survey and are discussed in Sections 3.1 and 3.2 below. Given the preliminary nature of our ongoing systematic survey of loess deposits, especially in the foothills of the Tian Shan, we will omit them from our discussion here.

3.1. Caves and rockshelters

During the 2017-2019 field seasons, we have located and recorded 95 cave and rockshelter features in our study regions (see Figure 7 and also Table 1 below). Of these 95 features, only ten were previously known, meaning that 85 have been discovered from our survey activity. As it was expected, the vast majority of these are in the Qaratau range, with two other, smaller groups in the Jungarian Alatau and Kazakh Altai. In terms of region, one surprise was the near total absence of prospective caves in the Kazakh Altai, where the presence of carbonates would have predicted a dense presence of suitable cavities. Cave systems in the southeast of Kazakhstan are very poorly known, even to speleologists (Shakalov, 2010), and the majority of the cavities encountered do not have significant amounts of sediment.

The archaeology discovered in the caves is still at a very preliminary stage. Only about a quarter of the caves and rockshelters recorded have some sort of sediment preserved (n=28), although many of those that do contain visible remains of Holocene archaeology. Test excavations were carried out at the 10 most promising localities, and are still ongoing at three of them. In general, the depth of sediments accumulated in the Holocene is quite large, between 1.5 and 2m, although not enough of them have been excavated down to bedrock to produce a statistically significant sample. When Pleistocene layers have been reached, the surface excavated has so far been too small to result in any obvious cultural or chronological assignations while radiometric dates are in processing. The presence of both caves containing sterile and occupied Pleistocene layers, however, is very promising for future predictions of landscape preference and occupation history in this region during the period of interest.

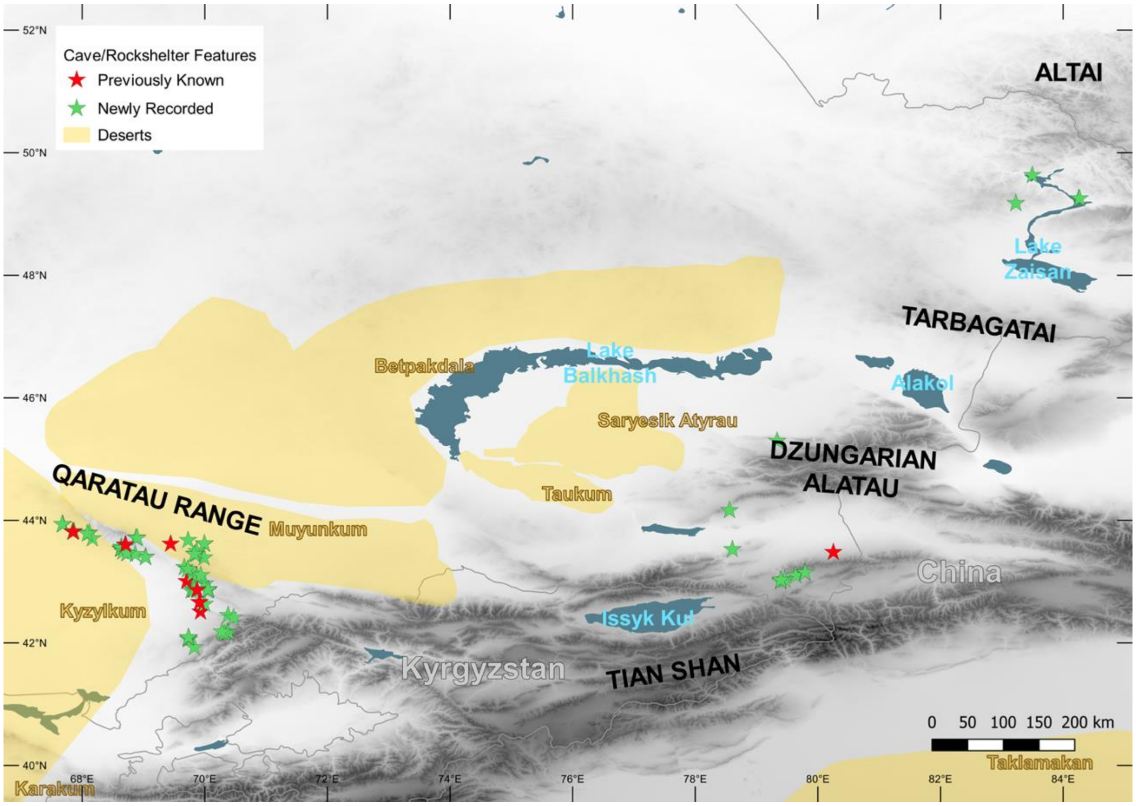

Figure 7. Caves surveyed by the PALAEOSILKROAD team from 2017-2019. A large number of the caves surveyed during this period have not previously been recorded, with a large proportion having been found in the Qaratau range. Including data from Global Administrative Areas (GADM) (Hijmans, 2012), Natural Earth, naturalearthdata.com, Shuttle Radar Topography Mission (SRTM) Version 4, (Jarvis et al., 2008)

Table 1. Tabulated karst and pseudokarst features with and without archaeology from survey seasons 2018-2019. *Based on surface/section finds and test-pit excavations in 10 features. **Based on stratigraphic observations (OSL and ^{14}C dating pending). NE: not excavated

Region	**Context**	**Total**	**Sediment**	**Archaeology (Holocene)***	**Archaeology (Pleistocene)***	**Pleistocene? (sterile)****
Qaratau	caves	67	23	14	2	4
	shelters	11	2	NE	NE	NE
Tian Shan/Jungarian Alatau	caves	11	2	NE	NE	NE
	shelters	2	1	1	1	0
Altai (Kazakh)	caves	0	0	-	-	-
	shelters	4	0	-	-	-
Total	caves	78	25	14	2	4
	shelters	17	3	1	1	0
Grand total		95	28	15	3	4

3.2. Spring sites

As discussed in Section 2.3, in terms of their location, springs in our study region frequently form along tectonic fractures (faults, joints, fissures), in which the water reaches the surface by following a natural course of voids or weakness in the bedrock under hydrostatic pressure. Following the fault mapping work by Grützner et al (2019), we focused on the survey of tectonically activated springs located in various areas of the Ili Basin and the Tarbagatai mountains. This relationship between tectonic faults, spring-fed rivers, and localities with surface lithics is particularly pronounced in a complex of sites on the northern side of the Tarbagatai mountains (see Figure 8). The springs and spring-fed rivers are associated with faults that run roughly east-west along the point in the landscape where the foothills meet the plains. Similar patterns were observed at the Tikenekti locality on the northern side of the Toraigyr mountains in the Trans-Ili Alatau. A cluster of lithics was found at the Tikenekti locality, in the foothills surrounding a spring (Figure 9). The spring is notable for being one of only two on this side of the Toraigyr mountains, the other being located approximately 5.8 km eastwards of Tikenekti. Altyn Emel, on the southern side of the Jungarian Alatau, follows a similar pattern between sites, faults, and springs. However, 12 km to the east-south-east the site of Basshy is unique among our spring sites in being associated with a series of springs that disgorge into the nearby plains, apparently from associated faults that may meet in the area beneath the overlying quaternary deposits.

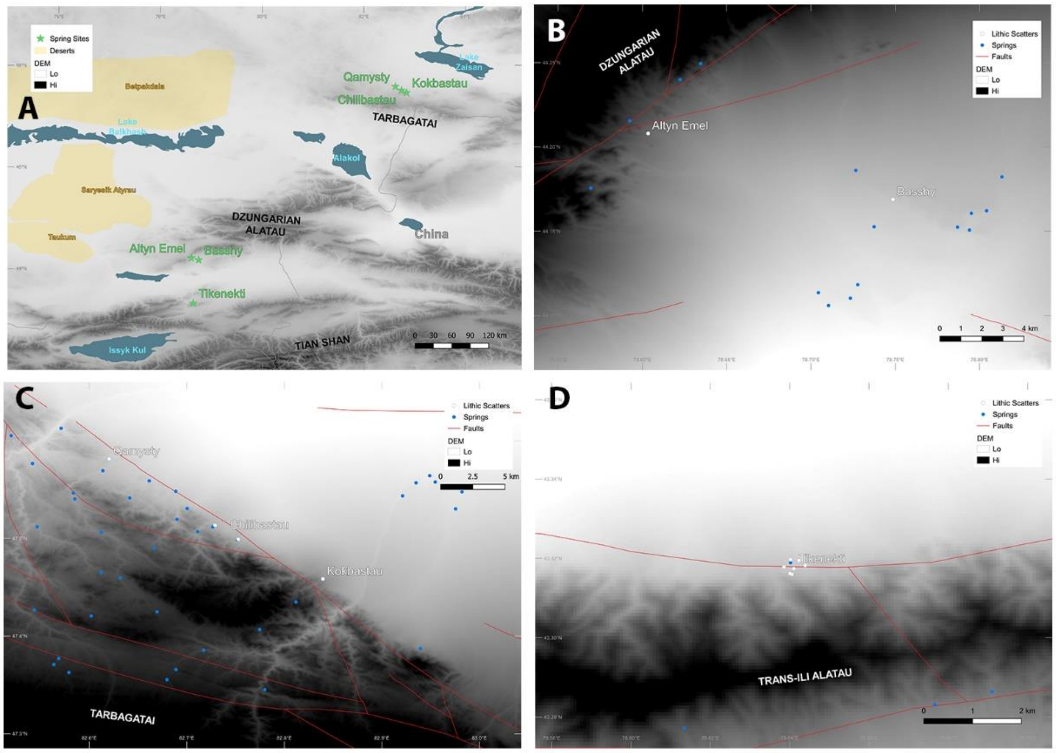

Figure 8 A) Overview of spring sites surveyed by the PALAEOSILKROAD team. This relationship between lithic scatters and springs has been observed north of the Tarbagatai range, and between the Dzungarian Alatau and the Tian Shan; B) spring sites of Altyn Emel and Basshy, on the south-eastern side of the Dzungarian Alatau, shown in relation to mapped springs and geological faults; C) spring sites along the north-eastern side of the Tarbagatai range, shown in relation to mapped springs and geological faults; D) spring sites in the locality of Tikenekti, surrounding a spring head. Shown in relation to other mapped springs and geological faults. Including data from Shuttle Radar Topography Mission (SRTM) Version 4, (Jarvis et al., 2008), Mineral Deposits Database and Thematic Maps of Central Asia (Seltmann et al., 2014).

The majority of the lithics found at the spring localities described above are non-diagnostic flakes and cores. Bullet cores typical of the Neolithic are sometimes found (e.g., at Kokbastau), although there is no reason to assume exclusively Holocene occupation. In fact, the diversity of the lithics found at these localities suggests instead that they were probably visited throughout the history of the springs themselves. Future excavations will show whether or not all the springs found on one fault share the same chronology and occupation histories.

Figure 9 The Tikenekti locality with lithic finds on the surface. The arrows indicate spots where individual lithics were found. The main concentration is on both sides of the spring head.

4. Discussion: possible biases in the archaeological record

Kast/pseudokarst, loess, and spring settings could constitute important contexts for archaeological investigation in the Kazakh IAMC. However, their diachronic formation processes demand special attention, since they induce specific characteristics and possible biases in the archaeological record. To begin with, caves are the most obvious landscape features for preserving archaeological sites, so they are perfect targets for systematic surveys. Moreover, they tend to have better organic preservation than open-air sites. However, as we saw in the previous section, efforts to locate Pleistocene archaeological sites in the Kazakh caves have so far had mixed results. We already stressed the importance of structural factors for cave evolution in Kazakhstan. Roof collapse events induced by structural instability bring contradicting implications for the preservation and discovery of archaeological sites in caves and rockshelters. On one hand, they produce an accumulation of tallus and big-sized rock fall debris that may seal occupation horizons as it has already been demonstrated for various well-known Paleolithic sites. Extensive collapse can also lead to the discovery of hitherto hidden caves (see Aqmeshit), while localized events can as well modify the morphology of the chambers and subsequently living space and human dwelling (see Tuttybulaq 1). The chimneys and fissures that often form as a consequence of roof collapse provide new pathways for sediment input into the cave. The impact of this mechanism for the development of thick cave sequences has been demonstrated in various case-studies inputting fine but also coarse sized surface materials underground (Jelinek et al., 1973; Goldberg et al., 2003). On the other hand, breaking through layers of rock fall presents significant logistical difficulties, especially in remote areas where manpower and technical support are hard to find.

Climate also plays a role in the accumulation of sediments in caves. In Kazakhstan, because of the semi-arid climate, slopes in areas of moderate to high relief are often erosional and mantled by the accumulation of unconsolidated rock debris (“scree”), in contrast with more humid climates, where slopes are mantled by a relatively thick soil cover (Frumkin et al., 2016). The increased solid fraction in relation to water in arid environments accumulates the sheets of coarse-sized debris at the foothills and valley sides forming talus (Karkanas & Goldberg, 2018). The amount and sheer size of material transported by the predominantly gravitational and free-fall flow processes described above is less likely to deposit fine sediment in cavities. Furthermore, it may lead to the erosion of caves and the masking of small shelters located at the base of slopes (Laville et al., 1980).

Based on our observations, the most common surface material that enters karst and pseudokarst features in Kazakhstan is aeolian loess. Topographic attributes including location, aspect, position, and slope morphology, as well as atmospheric circulation patterns like dust dynamics and wind direction greatly impact the deposition of this wind-blown sediment (Goldberg & Sherwood, 2006; Iovita et al., 2012). Therefore, we expect that local variations in loess cover (currently known on a very coarse scale, Figure 6) would determine the presence or absence of loess in natural cavities. Consequently, cavities lacking loess infill, especially in the case of limited autochthonous deposition, have a low probability of archaeological preservation.

In the case of pseudokarst features, on the other hand, the type of parent lithology seems to be the primary factor affecting the probability of sediment accumulation in the sheltered area. Based on our field observations, pseudokarst developed in sandstone constitutes the most promising setting for autochthonous geogenic sedimentation, which can ultimately lead to burial and preservation of archaeological remains.

As discussed above, loess deposits also constitute propitious archives for the preservation of archaeological sites. However, there are significant limitations that must be discussed. First, the thickness of loess cover suggests that many of the older parts of the landscape are irrevocably lost under massive amounts of sediment that can never be excavated completely. This presents a strong bias against older sites and may be the reason why no Middle Paleolithic sites have been so far discovered in loess in Kazakhstan. This brings us to the second point, which is visibility and landscape preference (e.g., Tryon, 2010). Loess sites are easy to identify in road cuttings or if preserved in river bank cliff deposits, because the whole sequence is visible and lithics, bones, and charcoal are often recognized during survey. However, not all such cuts and erosional features hide Paleolithic sites, and many Paleolithic sites undoubtedly lie completely undisturbed in unavailable landscape positions. For this reason, loess sites, like caves, present a very biased picture of landscape preferences of ancient humans. Likewise, they may distort arguments that rely on comparing distributions of sites by time period, as the older time periods will be underrepresented.

Loess cover in Kazakhstan is different from that of other regions in arid central Asia (see Figure 6), especially that encountered in China (Fitzsimmons et al., 2018; Sprafke et al., 2018). Unlike on the Chinese loess plateau (and also in Tajikistan), the thickness of the strata is influenced by the underlying topography (Sprafke et al., 2018) so that it is difficult to target a particular time period by field-walking near predetermined strata (e.g., see paleosols, see Zhu et al., 2018). Moreover, the problem of loess thickness affects the visibility of other traps that are relevant to Paleolithic archaeology, such as caves and rockshelters, which may be completely obscured by thick loess accumulations (see also Iovita et al., 2014 for a discussion of similar problems in southeastern Europe).

Coming to our final possible archive of past human activity in the IAMC, springs, we note that they can be found in each of our four study regions, allowing for possible comparisons and systematic targeting. However, so far we have identified several kinds of springs by discharge and origin types (Springer & Stevens, 2009), but we are unsure of the timing of their inception. It is possible that some of them are recently formed (in the Holocene) as a result of water table changes, others may be cutting through channels of extinct small rivers (that may themselves have been glacier-fed). For this reason, the lithics found on the surface in and nearby springs could be telling a variety of stories, some related directly to springs as a habitation site chosen by hominins, and others as agents of exposure of archaeological remains.

5. Future work

Understanding the processes that affect the preservation and visibility of Pleistocene archaeological record in IAMC is a challenging task and requires intensive fieldwork. In this paper we demonstrated not only that karst/pseudokarst, loess, and spring settings are prominent contexts for archaeological investigation in IAMC, but that they are each characterized by different attributes that impact their archaeological potential. A deeper understanding of the record formation requires analyses at both the site and landscape scale.

First of all, investigating further the sedimentary sequences recorded in some rockshelters and caves will provide an in-depth study of cave development and infilling. Ongoing dating and paleoenvironmental analysis of cave sediments will be integrated in paleoclimatic reconstructions, possibly correlated with the already well-established loess record. Ultimately, understanding the formation processes of karst and pseudokarst based on sedimentary and geomorphological criteria could evaluate the potential of those sites for human occupation through time. Comparing cave and loess sequences remains a distant goal for now, but one that we believe is achievable in the medium- to long-term.

In this context, it is important to explore further the relationship between faulting and cave development for specific areas of Kazakhstan. Should such a positive correlation be established, faults could provide a relative chronological marker for the formation of the caves and their structural evolution. Secondly, it would suggest the need for changing survey tactics for the discovery of new caves, putting focus on areas where mapped faults intersect the landscape. As it can be demonstrated in the area of Lesser Boraldai, faults are frequently perpendicular to river courses. Surveying along the course of rivers is a good survey strategy since rivers dissect the landscape and provide easy access to mountain passages and inter-mountainous valleys. Moreover, they may have formed cavities by eroding the bedrock and they would have offered access to fresh water to hominins and animals. Given the logistical difficulties involved in surveying deep canyons (low visibility from the bottom, difficult climbing), following fault lines and uplifted uplands could provide an auxiliary survey solution.

In order to increase the probability of finding Paleolithic occupation in proximity to springs, it will be necessary to focus on areas that promote the formation of more stable spring channels. Perennial springs, which sustained freshwater discharge during the climatic fluctuations of the Late Pleistocene should have been significant landmarks for hominins. The more frequent visits to these localities, as opposed to those with more ephemeral springs, should therefore translate to a higher accumulation of cultural material. According to Cartwright and Johnson (2018), the stability of spring discharge is determined by type of recharge, flow-path length, groundwater volume and residence time. They specifically note that large-volume springs with relatively stable discharge are commonly associated with extensive, high-primary-permeability geologic units or with geologic structure and faulting that provide secondary permeability in the aquifer. In their discussion, long term springs are often characterized by extensive underground flow paths and long-term mean residence times that can span decades or even centuries.

Last but not least, improving our rate of success in discovering loess sites will likely depend upon intensive foot surveys of specific valleys, to obtain more data on the relationship between landscape position and the probability of site discovery.

6. Conclusions

A combination of paleoanthropological, geographic, and paleoclimatic factors strongly suggests that a corridor roughly similar to what we now call the Silk Road likely existed during the Pleistocene. Whether hominins used this corridor for dispersal throughout the last glacial cycle or not remains still to be evaluated through extensive archaeological fieldwork. In this article, we have attempted to evaluate the chances of that fieldwork yielding the results we need for modeling hominin behavior. From our field observations, it is clear that the archaeological record has some in-built biases, which will be difficult to overcome even by systematic survey. First, the main targetable archives are geographically not equally distributed. Karstic features, our best hope for good organic preservation and longer sequences that could be used to evaluate long-term human occupation, are present in two clusters more than 1000 km apart, (in the Qaratau and the Jungarian/Trans-Ili Alatau). Although piedmont loess covers much of the area in between these two clusters, it remains difficult to find sites because of the limited number of exposures, which mostly occur in the form of road cuts or river banks. Moreover, the sites that have been found so far in loess have been only Upper Paleolithic in age, thus missing the earlier part of the record of interest. Given that typologically Middle Paleolithic lithics are known from deflated contexts elsewhere in the country, we expect stratified Middle Paleolithic sites to be there, but probably deeply buried. This could be a reason for the pattern we have previously reported in our review (Fitzsimmons et al., 2017, Fig. 8), where cave and rockshelter settings in Central Asia preserve older occupations. Finally, we have found ample evidence for Stone Age occupation nearby springs and documented patterns of association between springs and fault lines, which we plan to use to plan future surveys.

In conclusion, the search for a Paleolithic Silk Road through Kazakhstan is just beginning. Although we remain optimistic about the region's archaeological potential, we would like to caution, at least for now, against grand theories of cultural diffusion or actual dispersals often illustrated by 'drawing arrows on maps'.

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RESEARCH ARTICLE

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The effect of formation processes on the frequency of palaeolithic cave sites in semiarid zones: Insights from Kazakhstan

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Abstract

Central Asian caves with Palaeolithic deposits are few, but they provide a rich record of human fossils and cultural assemblages that has been used to model Late Pleistocene hominin dispersals. However, previous research has not yet systematically evaluated the formation processes that influence the frequency of Palaeolithic cave sites in the region. To address this deficiency, we combined field survey and micromorphological analyses in the piedmont zone of south Kazakhstan. Here, we present our preliminary results focusing on selected sites of the Qaratau mountains. Sediment cover varies among the surveyed caves, and loess-like sediments dominate the cave sequences. The preservation of cave deposits is influenced by reworking of cave sediments within the caves but also by the broader erosional processes that shape semiarid landscapes. Ultimately, deposits of potentially Pleistocene age are scarce. Our study provides new data in the geoarchaeologically neglected region of Central Asia and demonstrates that micromorphology has great analytical potential even within the limitations of rigorous survey projects. We outline some of the processes that influence the formation and preservation of cave deposits in Kazakhstan, as well as broader implications for the distribution of Palaeolithic cave sites in Central Asia and other semiarid environments.

KEYWORDS

cave sediments, Central Asia, geoarchaeology, Kazakhstan, micromorphology

1 | INTRODUCTION

Within the approximately four million square kilometres that span the five Central Asian Republics of Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan, only 18 caves document Palaeolithic occupation (see Figure 1). These sites are located in the intermontane basins and river valleys that shape the foothills of the high-altitude Central Asian mountain massifs. The Russian Altai, located at the northern fringes of Central Asia, have the highest frequency of Palaeolithic cave sites in the region, with a geographically restricted cluster found along the tributaries of major rivers. Further south, isolated Palaeolithic cave sites have been found in Kazakhstan, Kyrgyzstan and Tajikistan, while the second cluster of sites is reported along the Alay mountains in Uzbekistan. The Palaeolithic occupation of Central Asian caves ranges from the Middle to the Upper Palaeolithic, and despite their low numbers, in many cases, they have provided rich cultural assemblages and human remains (see Table S1). Analysis of these palaeoanthropological remains has led to novel genetic discoveries regarding human evolution, such as the identification of the Denisovan hominin group (Krause et al., 2010; Reich et al., 2010; Slon et al., 2018). Building upon this record and in combination with data from open-air sites, various studies have attempted to model the presence of hominins in the Central Asian landscape (Beeton et al., 2014; Glantz et al., 2018; Iovita et al., 2020; Li et al., 2019). It seems that the foothills that connect the Central Asian mountains towards the West and the desert/steppe zones towards the East form an Inner Asian Mountain Corridor (IAMC; Frachetti, 2012) that may have served as a likely location of hominin refugia (Beeton et al., 2014; Glantz et al., 2018). Especially during glacial conditions, a 'northern' route along the foothills of the IAMC appears as the sole most likely scenario for hominin dispersal across Central Asia (Iovita et al., 2020; Li et al., 2019).

Even though these models provide important implications regarding the distribution of Palaeolithic sites in Central Asia, their accuracy is limited by the quality and quantity of the available data set. In particular, the Russian Altai is the only well-studied area in the region, being the subject of multidisciplinary research since the 1980s (Derevianko et al., 2018, p. 303). However, survey and excavation projects have been fewer south of the Altai, where the relative absence of systematic survey may have implications for the low distribution of cave sites (Fitzsimmons et al., 2017). We know little about the formation processes of the archaeological record in this region, since a high-resolution contextual methodology has been applied only on selected sites associated with hominin remains. In those cases, geoarchaeological approaches using a microanalytical methodology (Mallol et al., 2009; Morley et al., 2019) or broad-scale observations (Derevianko et al., 2018; Krivoshapkin et al., 2020) have significantly aided our understanding of geogenic deposition, anthropogenic impact and local environmental change. These studies have broader archaeological importance since the analysis of cave sediments in arid to semiarid environments, like Central Asia, is rather limited. In this context, we stress that our picture for Late Pleistocene Central Asia is made up of only a few individual well-studied cases, extrapolated models and limited knowledge of the processes that govern the archaeological record on a regional scale.

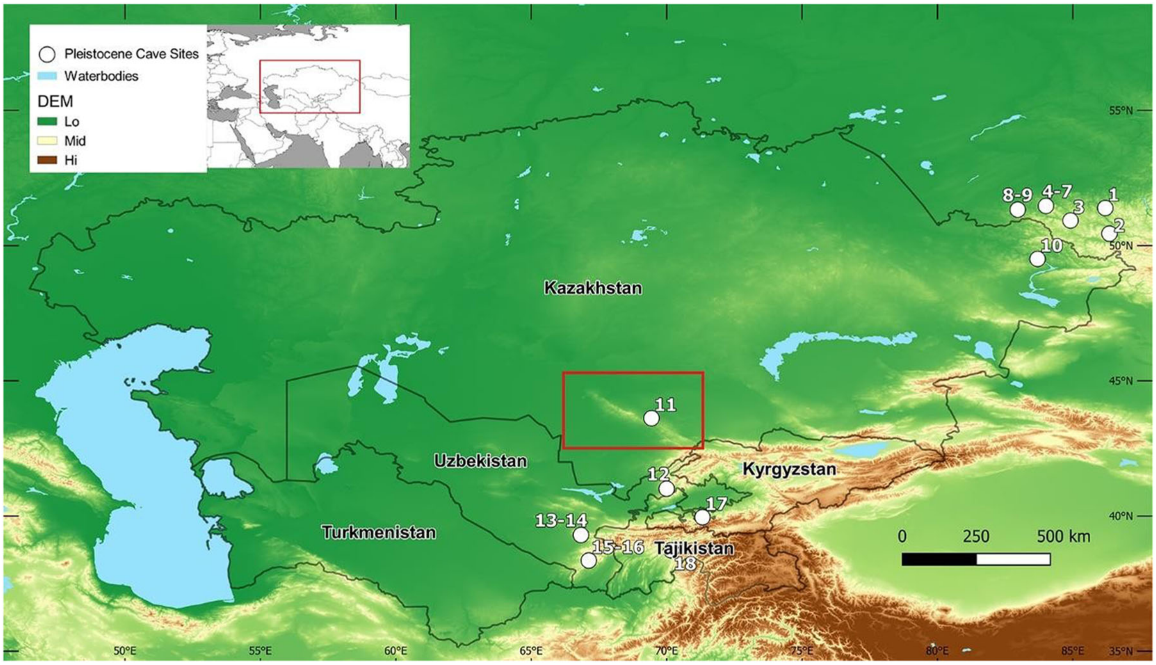

FIGURE 1 Previously known Pleistocene archaeological cave sites in Central Asia. (1) Byka cave complex. (2) Maloyalomanskaya. (3) Ust'-Kanskaya. (4) Iskra cave. (5) Okladnikov (Sibiryachikha). (6) Denisova. (7) Kaminnaya. (8) Chagyrskaya. (9) Strashnaya. (10) Bukhtarma cave. (11) Ushbas. (12) Obi-Rakhmat. (13) Anghilak. (14) Aman Kutan. (15) Amir-Temir. (16) Teshik-Tash. (17) Sel'ungur. (18) Ogzi-Kichik. For references, see Table S1 [Color figure can be viewed at wileyonlinelibrary.com]

To change this picture, we require more field data to help us understand how the interaction between hominins and geomorphic environments shaped the unique Late Pleistocene archaeological record along the IAMC. In our recent paper (Iovita et al., 2020), we presented preliminary results of the 2017–2019 survey in Kazakhstan and attempted to evaluate some taphonomic biases that influence the distribution and quality of archaeological sites in the region. Here, we build further upon that study to explore the occurrence and characteristics of cave sediments in South Kazakhstan. First, we present statistics on the presence of sediment in caves and rockshelters based on the total number of features surveyed and test-excavated by our team. To assess the completeness of our data set, we utilise observations on cave morphology to examine the potential erosion of pre-existing sediments. Second, we focus on the Qaratau mountains and combine field stratigraphy with micromorphology to explore the depositional processes operating at different cave sites within that range.

1.1 | The Qaratau mountains in the context of the Inner Asian Mountain Corridor (IAMC): Geographic setting and geology

The IAMC constitutes a 2500 km-long chain of mountain foothills (piedmonts) flanked by lowland deserts (e.g., Qyzylqum Qaraqum Moyunqum, Tauqum, Saryyesik-Atyrau) and high mountains (the Pamir, Alay, Tian Shan, Dzungar and Altai), extending from Afghanistan to southern Siberia (see fig. 1 in Iovita et al., 2020). The majority of stratified Palaeolithic sites in Central Asia are found in this piedmont zone, which appears to have functioned as an ecological niche fostering hominin dispersals (Beeton et al., 2014; Glantz et al., 2018; Li et al., 2019; Zwyns et al., 2019). About half of the area of the IAMC falls within the modern territory of Kazakhstan, whose Palaeolithic settlement patterns remain relatively understudied (Cuthbertson et al., 2021). Complex and tectonically active landscapes, such as the Kazakh piedmonts, would be attractive for Palaeolithic hunter-gatherers since they provide availability of water, shelter and rich animal and plant resources in contrast to the desert and steppe lowlands that dominate the regional topography (Bailey & King, 2011; Winder et al., 2015). However, the Kazakh piedmonts could also be attractive for archaeologists since they preserve archaeological sites in different geomorphic contexts such as caves, loess-mantled slopes and springs (Iovita et al., 2020). Loess sediments dominate the Quaternary deposits in this piedmont zone, providing both a potential sediment source for the formation of archaeological sites and a palaeoenvironmental archive (Fitzsimmons et al., 2017). By conducting a thorough survey of carbonates in four distinct regions of the Kazakh piedmont, our team concluded that the majority of surveyed caves, including the caves presented in this study, are found in the Qaratau mountains (Cuthbertson et al., 2021; Iovita et al., 2020).

The Qaratau mountain range is located in South Kazakhstan, delimited by the Qyzylqum desert, the Syr Darya and Arys rivers to the West, the Chu-Sarysu basin and Moyunqum desert to the East, the South Turgay basin to the North and the Tian Shan Mountains to the South (Figure 2). It has a NW-SE trend and is divided into two ridges: the Lesser Qaratau in the southeast and the Greater Qaratau in the northwest. Overall, the Qaratau mountains constitute a Northern segment of the major Talas-Fergana fault (Alexeiev et al., 2017; Burtman, 1980), with their evolution tied to the broader patterns of Central Asian tectonics (e.g., Kirscher et al., 2013).

Some of the oldest and most abundant rock types found in the Qaratau mountains include siliciclastic and volcanic rocks of Neoproterozoic age, as well as Middle and Upper Ordovician marine carbonates and granitoids. Towards the Middle Palaeozoic, volcanism and sedimentation in the region were generally associated with the passive margin development that contributed to the progressive amalgamation of the Palaeo–Kazakhstan continent (Biske, 2015). Regarding these changes, the formation of a carbonate platform from the Late Devonian until the Middle Carboniferous testifies to the presence of the Turkestan Ocean in the vicinity of the Qaratau and marks a new period of carbonate deposition in the area. This carbonate sequence is about 4 km thick, outcrops frequently throughout the mountain range and consists of depositional facies with diverse lithology (Cook et al., 2002). The geological picture of the area changed drastically after the Late Carboniferous, when major deformation events led to marine regression, termination of carbonate sedimentation and uplift (Alexeiev et al., 2009). Continental accretion culminated during the Late Palaeozoic, resulting in the closure of the Palaeo–Asian ocean and the formation of the Central Asian Orogenic Belt (Windley et al., 2007). Successive reactivations of the Talas-Fergana fault during the Mesozoic and Cenozoic induced additional deformation in the Qaratau. In the Jurassic, an elongated depression (Leontiev Graben) formed between the Greater and Lesser Qaratau, accumulating coal-bearing lacustrine and fluvial sediments (Alexeiev et al., 2017; Allen et al., 2001). In the Cenozoic, the collision between India and Eurasia about 50–35 Ma initiated substantial orogeny, with modern Tien Shan relief developing after ~3 Ma (Buslov et al., 2008; Trifonov et al., 2008). The interplay between Quaternary climatic evolution and local neotectonics dramatically changed the environments of East Kazakhstan. Glaciations and increased aridification led to extensive deposition of glacial and aeolian sediments covering intermontane basins and their adjacent foothills (Aubekerov, 1993; Chlachula, 2010).

In contrast to other parts of Central Asia and Kazakhstan, the major uplift in the Qaratau enables the exposure of pre-Cenozoic structures that would otherwise be masked by recent sediments (Allen et al., 2001, p. 84). This setting facilitates the survey of the karst-forming Palaeozoic carbonate sequence and provides implications for the clustering of caves and rockshelters in this part of Kazakhstan. The limited speleological work in the region demonstrated that cave formation in some parts of the Qaratau is associated with Carboniferous karst massifs and plateaus shaped by tectonics (Shakalov, 2010, 2011).

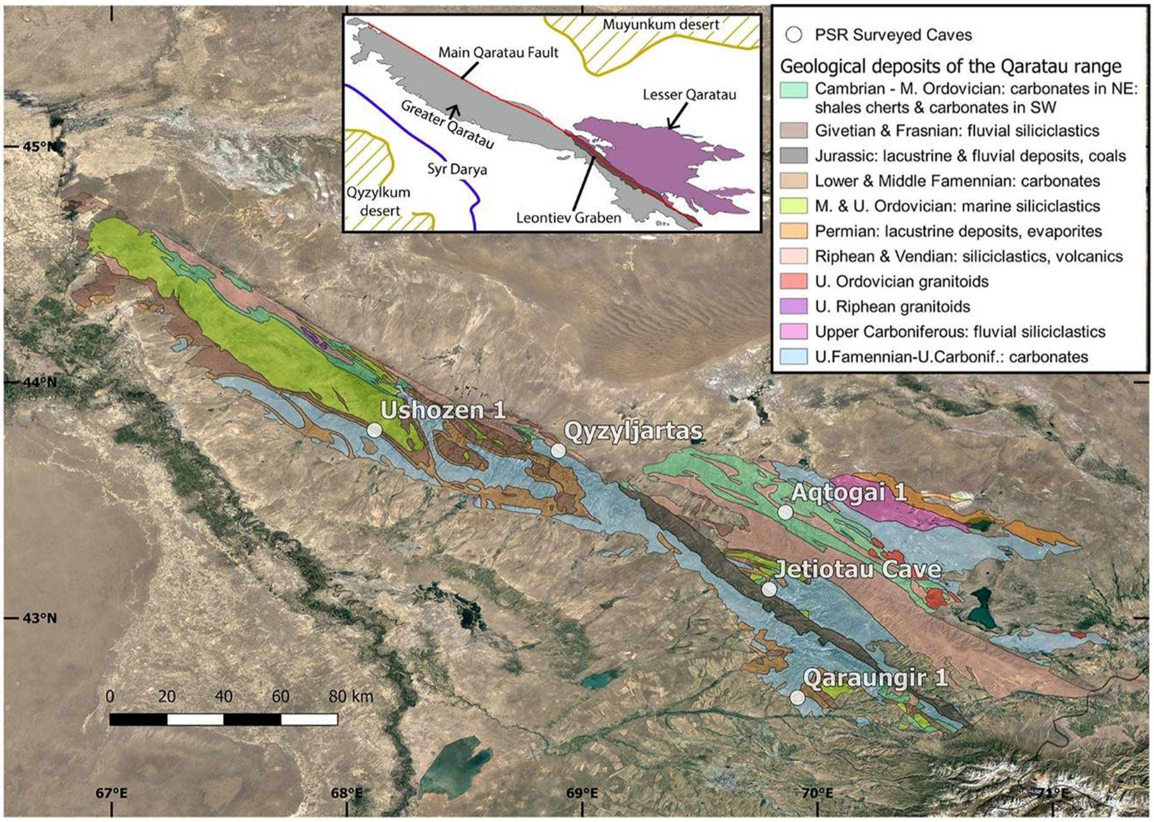

FIGURE 2 Geological map of the Qaratau mountain range with the sites analysed in the text with micromorphology. The map extent corresponds to the red bounding rectangle of Figure 1. The sketch map depicts the main tectonic structures mentioned in the text. Geological deposits adapted from Alexeiev et al. (2009; fig. 1). Note the complex piedmont topography along the Qaratau mountain front as opposed to the surrounding deserts and steppe lowlands. Imagery ©2021 TerraMetrics, Karatau Range Kazakhstan @43.5235, 69.2049, https://www.google.com/maps/ [Color figure can be viewed at wileyonlinelibrary.com]

1.2 | Micromorphology in a survey context

Archaeological micromorphology is an established geoarchaeological technique that addresses a vast array of questions regarding the formation processes of deposits by studying thin sections of undisturbed sediments (Courty et al., 1989; Macphail, 2014; Nicosia & Stoops, 2017). It is often applied in well-documented sites and long-term excavation projects in the framework of a high-resolution approach that requires thorough sampling (e.g., Goldberg et al., 2018; Karkanas & Goldberg, 2010; Macphail, 1999; Miller, 2015), and often additional microcontextual techniques (e.g., Albert et al., 2012; Mentzer, 2014; Milek & Roberts, 2013). As a survey project, we decided against this high-resolution approach since (1) we aimed for a broad investigation of caves and rockshelters in our survey area, rather than focusing on a long campaign of excavating a single site, and (2) we could not apply an exhaustive range of analytical techniques because of logistical constraints on time in the field, as well as transport and storage during long survey campaigns. Instead, we used micromorphology selectively to gain a plethora of contextual information within promising sites, to interrogate difficult stratigraphic relationships and to establish a connection between landscape and site-specific processes. While the micromorphological results presented here are not exhaustive and do not aim to reconstruct the whole range of formation processes operating at a given site, they provide preliminary insights into the characteristics of the excavated sequences by highlighting the dominant depositional factors that operate at these different localities.

2 | METHODS

2.1 | Survey methodology

The caves and rockshelters presented here were surveyed and recorded during our recent fieldwork in Kazakhstan (Iovita et al., 2020). The surveys were structured around a novel modelled approach (Cuthbertson et al., 2021) that used supervised and unsupervised landform classification, as well as the spatial extent of near-surface limestones and carbonates (CERCAMS; Seltmann et al., 2014), to generate predictive mapping for areas of potential karstic feature formation. These models informed the targeted field survey, during which the features were identified. Caves and rockshelters are typically found in the mid-slope position of steep and high slopes that bound deep valleys (Cuthbertson et al., 2021). For the on-site recording of features, we used an adapted version of the PaleoCore data structure (PaleoCore.org; Reed et al., 2015, 2018), and focused primarily on morphological attributes that were likely to be useful for further archaeological and geological investigations (e.g., sediment presence, cave morphology, speleothems). Most of the caves in our study area are single-chambered caves, and their formation history appears to be closely related to tectonics. For more information on cave and rockshelter morphology in our study area, see Iovita et al. (2020).

2.2 | Sediment occurrence, stratigraphic documentation and micromorphology

A primary goal of our survey was to test the archaeological potential of caves in Kazakhstan. We used sediment thickness in individual caves as a guide to focus on prominent sites, based on the assumption that thicker cave sequences would have higher chances of preserving archaeological deposits or Pleistocene sediments. The influence of modern cave use in the formation of the archaeological record has not been documented in Kazakhstan in the past. However, ongoing ethnographic work by our team demonstrates that caves are mostly associated with religious practices that do not heavily rework the deposited sediments (Bigozhin et al., unpublished data). Because caves are rarely used for pastoral activities like stock-keeping, distinct stabling deposits, which are common in other parts of the world (e.g., Angelucci et al., 2009), were not found during field survey. Reworking of older cave sediments is documented only at the site of Tuttybulaq 1, induced by smelting activities dating to the medieval period (Baytanaev et al., 2017, 2018, 2020). Therefore, by documenting sediment characteristics across different caves, we built a regional data set of cave sediment distribution that serves as a basis for exploring the depositional and erosional processes that influence the formation of the cave record.

To explore the potential erosion of pre-existing sediments in empty caves, we focused on the recording of specific morphological characteristics that could indicate erosional events in the interior and the exterior of karst features. Regarding the interior of karst features, we searched for past cave surface levels, remnant sediment pockets (unconsolidated or cemented) and evidence for the differential weathering of cave wall surfaces induced by sediment removal (O'Connor et al., 2017). Turning to the exterior of karst features, we investigated the adjacent topography to identify rockfall and debris accumulations (e.g., talus slopes) that could be associated with large-scale erosion of the features themselves.

For caves with sediment, we classified sediment thickness in both unexcavated and excavated features. In unexcavated features, we estimated sediment thickness as a minimum value from field observations of cave morphology, and where possible, we used a dynamic cone penetrometer (Kessler Soils Engineering, Inc.; Model K100) to verify our assessments. For excavated caves, we documented sediment thickness based on older publications or from our new test trenches. Our classification scheme was heuristic and used three levels of sediment cover: caves with 'Minor' deposits (<0.5 m), 'Moderate' deposits (>0.5 m) and 'Significant' deposits (>2 m). We then used our data on sediment thickness to systematically test excavate promising caves, aiming to explore site-specific depositional factors. For the documentation of the excavated sections, we defined lithostratigraphic units (LUs) following standard lithostratigraphic descriptions that focus on textural attributes and sedimentary structures. To facilitate comparison and synthesis between the deposits of different caves, the stratigraphic nomenclature is followed by the initials of each cave (e.g., LU J4 corresponds to the LU 4 from Jetiotau cave). Macroscopic descriptions of the excavated stratigraphic sequences are presented in Table S3. In addition to macroscopic observations, we collected micromorphology samples from selected LUs. The micromorphological thin sections were subsequently divided into microstratigraphic units (MUs). Again, for comparative purposes, the MUs are named after LUs. For example, MU J4-1 corresponds to the first MU of LU J4.

2.3 | Thin-section preparation procedure and analysis

The micromorphology samples were encased in plaster, and after extraction, were wrapped with paper and packaging tape to ensure integrity during transport. Thin sections were produced in the Geoarchaeology Laboratory at the University of Tübingen and Terrascope Thin Section Slides. Initially, the samples were dried in an oven at 40°C and impregnated with a mixture of polyester resin, styrene and methylethylketone peroxide (MEKP) hardener under vacuum. After a period of around 20 days, the block samples reached the required hardness and were sliced into slabs with a rock saw. The thin-section production procedure ended with the mounting of the slabs onto 6 × 9 cm glass slides, and then grinding of these slabs to about 30 μm thickness. For some samples, a third mounting or hand polishing was necessary to obtain the right thickness. The thin sections were initially scanned using a high-resolution flatbed scanner to be documented and examined macroscopically (Haaland et al., 2019). Afterwards, they were studied under a stereoscope (0.65 – 5× magnification) as well as a petrographic microscope (20–500× magnification) using plane-polarised light (PPL), cross-polarised light (XPL) and oblique incident light. Micromorphological descriptions follow the nomenclature and criteria proposed by Stoops (2003) and Courty et al. (1989) and are presented in Table S4. Thin sections were also examined under a fluorescent microscope equipped with the Zeiss Colibri system by using the 470 nm filter to test for phosphate and the 555 nm filter to test for organics.

3 | RESULTS AND INTERPRETATIONS

During the fieldwork seasons of 2017–2019, we surveyed a total of 95 caves and rockshelters (Table S2). Sixty-seven features are devoid of sediment and 28 have a varying degree of sediment cover. Out of the 28 features, eight caves had already been excavated in the past;

TABLE 1 List of excavated caves in the Qaratau mountains

Site name	Archaeology	Excavation data
Aqtogai 1[a]	Holocene Pleistocene (?)	Shunkov et al. (2018); PSR (2019; unpublished survey data)
Hantagi 1	Holocene	Z. Taimagambetov (personal communication)
Jetiotau[a]	Holocene (?) Pleistocene (?)	PSR (2018; unpublished survey data)
Marsel Ungiri	-	PSR (2019; unpublished survey data)
Mayatas	Holocene	Shunkov et al. (2018)
Qaraungir 1[a]	Holocene	Taimagambetov and Nokhrina (1998); PSR (2019)
Qyzyljartas[a]	Pleistocene (?)	PSR (2018; unpublished survey data)
Temir 2	Holocene Pleistocene (?)	PSR (2019; unpublished survey data)
Tuttybulaq 1	Holocene Pleistocene (?)	Baytanaev et al. (2017, 2018); PSR (2019; unpublished survey data)
Tuttybulaq 2	Holocene	Baytanaev et al. (2017); PSR (2019; unpublished survey data)
Uhbas 1	Pleistocene	Alpysbaev (1961); Grigoriev and Volkov (1998); PSR (2018; unpublished survey data)
Ushozen 1[a]	Holocene	PSR (2018; unpublished survey data)
Yntaly 3	Holocene	G. Iskakov (personal communication)

Note: Notice the abundance of Holocene archaeology among the excavated caves. Pleistocene sediments followed by (?) indicate potential chronology, since confirmation by absolute dating is pending. Excavations in most localities have not yet reached bedrock. For the locations of the caves, see the supplementary material in Cuthbertson et al. (2021). PSR refers to the PALAEOSILKROAD project.

[a] Caves with micromorphological results presented in this study.

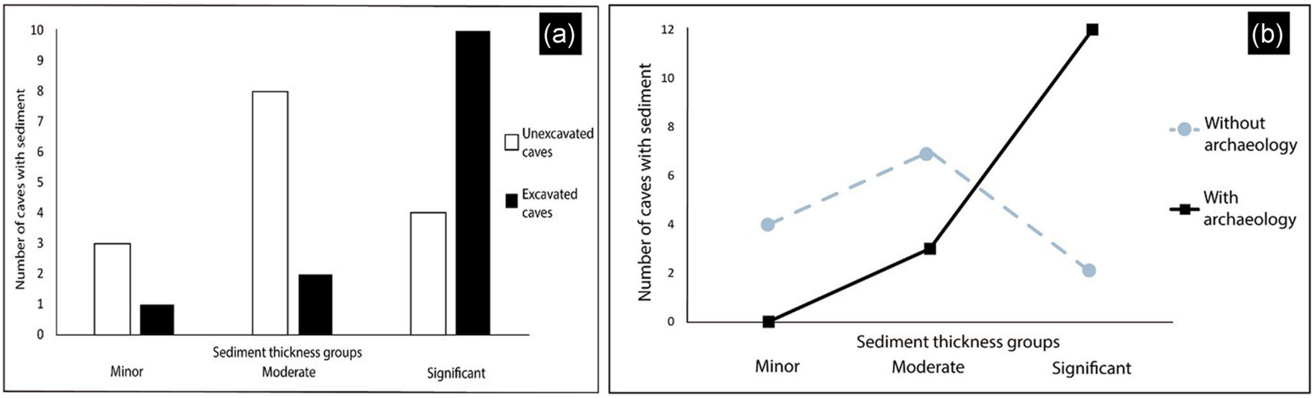

FIGURE 3 Characteristics on the presence of sediments in caves and rockshelters surveyed by our team during the 2017–2019 seasons. (a) Excavated and unexcavated features with sediment (*N* = 28) grouped by sediment thickness. The sediment thickness classification is based on a combination of surface morphology, penetrometer measurements and excavation data (where available). The sediment thickness groups are as follows: minor: <0.5 m; moderate: >0.5 m; and significant: >2 m. (b) Occurrence of archaeology among the different sediment thickness groups. Dotted line: features without archaeology. Solid line: features with Holocene or Pleistocene archaeology (see also Table 1) [Color figure can be viewed at wileyonlinelibrary.com]

we conducted test-excavations in 10 caves in total, including five newly documented caves (Table 1). To obtain an overview of the characteristics of the sediment cover, we classified sediment thickness in both unexcavated and excavated features (Figure 3a). Our findings demonstrated that only four features have 'Minor' deposits of <0.5 m, while most of the surveyed localities range between the 'Moderate' (>0.5 m) and 'Significant' (>2 m) sediment thickness categories, with 10 and 14 features, respectively. Caves with thicker sequences also tend to contain archaeological materials (Figure 3b). Most of the archaeological materials recovered in our excavations appear to date to the Holocene, and Pleistocene materials are scarce (Table 1).

Here, we present our observations from the field and results of micromorphological analysis from five caves of the Qaratau mountains (Jetiotau, Qyzyljartas, Ushozen 1, Qaraungir 1 and Aqtogai 1; Figure 2, Table 1, Figure S1). We selected these five caves since their diverse sequences provide an overview of the major processes that seem to influence the formation of cave sites in the region.

3.1 | Jetiotau

The Jetiotau cave is located ~2 km north-east from the Janatalap village of the Baidibek district, Turkestan region. It is formed on Lower Carboniferous (Tournaisian) carbonates at the South Western part of the lesser Qaratau, adjacent to the fault zone forming the Leontiev graben. It has a NW-SE orientation and a tube-shaped morphology consisting of a single 30 m-long passage with a maximum roof height of ~7 m (see also Figure S2a).

3.1.1 | Stratigraphic overview

In Jetiotau, we excavated a 3 × 1 m test trench at the entrance area of the cave, exposing a stratigraphic sequence of 2.12 m without reaching bedrock (Table S3). The excavated deposits are generally brown to light olive brown with a silty clay to clay loam texture, while layer boundaries are mostly wavy and occasionally sharp. Angular limestone roof-spall clasts are the predominant inclusion present and mainly demonstrate random distribution and sorting. However, their frequency and size range vary, with more clasts occurring in LU J3 and LU J5. Although bone and charcoal fragments were found in low quantities scattered among different LUs, artefacts such as pottery or lithic tools were absent. Nevertheless, the well-defined transitions between clast-rich and clast-poor deposits at Jetiotau warrant further investigation since they may reflect changes in sedimentary input or different formation processes. The complex formation processes recorded at Jetiotau (see the micromorphological analysis below) indicate different cycles of deposition and reworking, which could potentially suggest that parts of the excavated sequence are of Pleistocene age. Pending OSL dates will provide a chronological constraint for the depositional changes at Jetiotau.

3.1.2 | Micromorphology

Two micromorphology samples were collected from the northern section of the test trench. Sample PSR-18-2 covers the contacts

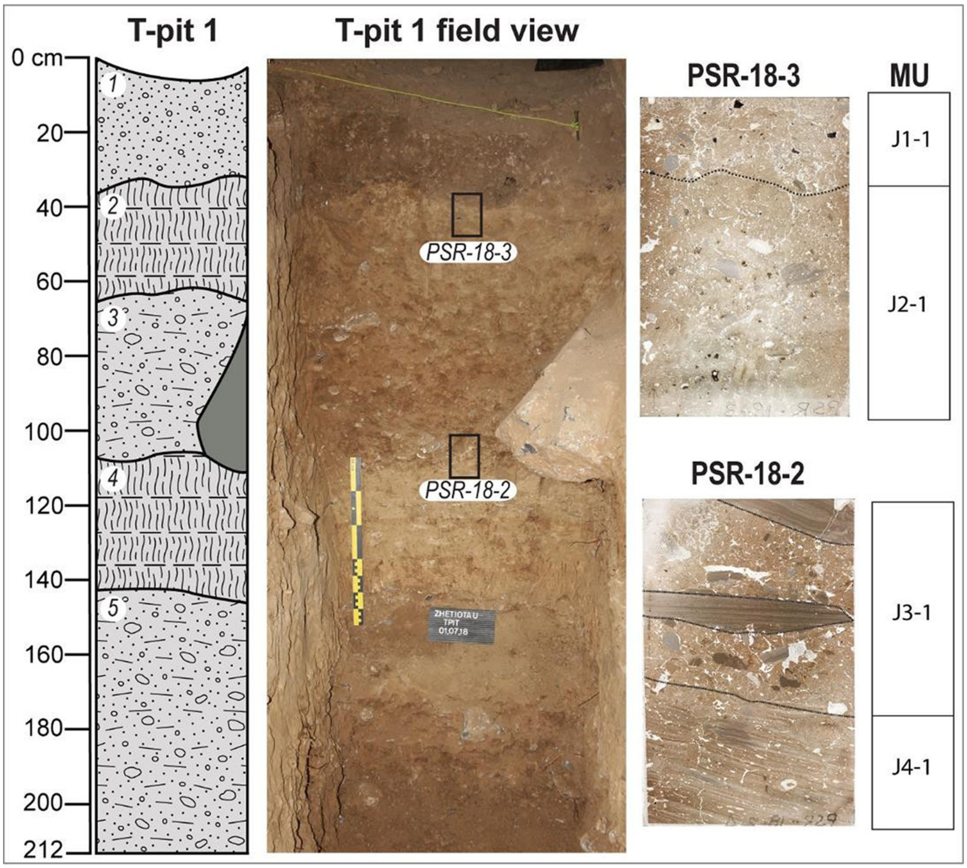

FIGURE 4 Stratigraphy and micromorphology in Jetiotau cave. Circled numbers indicate lithostratigraphic units: (LU J1) clay loam; (LU J2) silty clay loam; (LU J3) clay loam; (LU J4) silty clay; and (LU J5) clay loam. Black frames show the locations of micromorphological samples accompanied by a scan of the thin section (in PPL) and MU classification [Color figure can be viewed at wileyonlinelibrary.com]

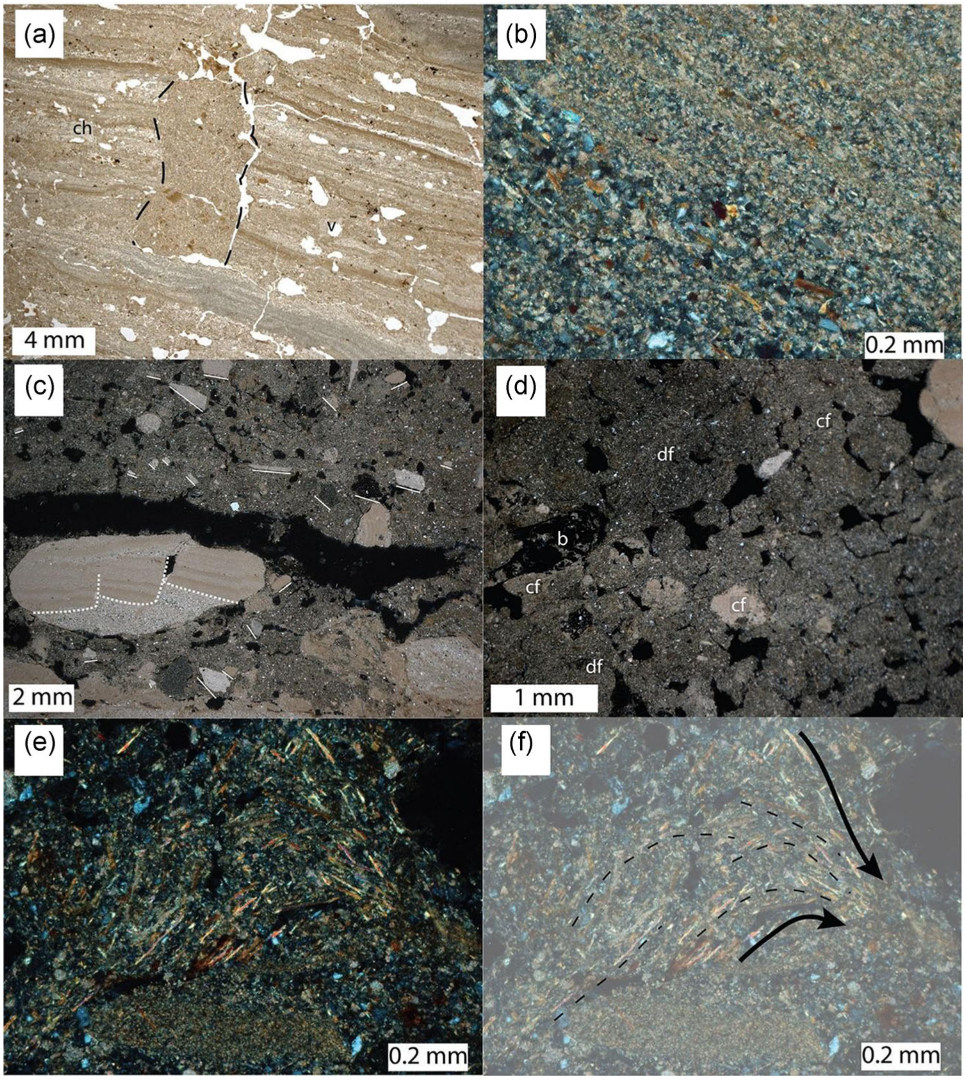

FIGURE 5 Microphotographs from Jetiotau cave. (a) MU J4-1. Note: laminated bedding dipping towards SW and complex microstructure consisting of vesicles (v) and channels (ch). Dotted lines outline a burrow breaking through laminae; PPL (b) MU J4-1 laminae. Note the oblique orientation of mica grains following the inclination of the deposit and grading; cross-polarised light (XPL). (c) MU J3-1. Note the oblique to horizontal orientation towards the SW for the majority of coarse sand and gravel-sized clasts (white solid lines). White dotted lines indicate slumping of a laminated clast; XPL. (d) MU J2-1. Mixing of calcitic–crystallitic aggregates and matrix (cf) with decalcified and phosphatised (df) b-fabric. A partially cemented bone fragment (b) is also present; XPL. (e and f) MU J3-1. Photomicrograph and sketch of a rotational micro-deformation feature showing the preferential distribution, orientation and alignment of mica particles. Dotted and solid lines indicate the general flow direction; XPL [Color figure can be viewed at wileyonlinelibrary.com]

between LUs J3 and J4, while PSR-18-3 covers the contact between LUs J1 and J2. MU J4-1 comprises a laminated structure at the basal part of sample PSR-18-2 (Figures 4 and 5a) that demonstrates the effects of water action in the formation of the upper part of LU J4. This deposit mainly consists of micrite with the addition of well-sorted silt, sand-sized quartz and mica grains in the coarser laminae. The fluctuating composition of the laminae is indicative of sheetwash processes (Karkanas & Goldberg, 2018), while the parallel to subparallel orientation of mica grains (see Figure 5b) also suggests deposition in a low-energy water-lain environment (Mücher & Ploey, 1977). Nevertheless, water flow was not constant during the formation of the laminated sequence. Phases of non-saturation are evidenced by the presence of intrusive yellowish-brown dusty clay coatings, burrows and elongated planar voids likely associated with cycles of wetting and drying. MU J4-1 is the only deposit in our studied sites heavily reworked by aqueous processes. This extensive reworking indicates fluid circulation at the cave entrance or reactivation of the karstic network.

MU J3-1 is a coarse and heterogeneous deposit overlying MU J4-1. It covers the rest of sample PSR-18-2 and correlates with the clast-rich LU J3. Under the microscope, this deposit is indeed clast-supported and comprised primarily of poorly sorted and randomly distributed clasts. The geogenic coarse material consists of limestone fragments, sand-sized mica, quartz and laminated clasts that constitute the most abundant aggregate. Some of the laminated clasts show similarities to MU J4-1 while others have a more microsparitic texture. In both cases, they represent remobilised material originating from within the cave. The coarse material shows a moderately expressed parallel to oblique orientation (Figure 5c). In terms of biogenic inclusions, we recorded phosphatised pellets, carnivore coprolites and a few bone fragments (Figure 14a). Finally, it is also important to note the weakly developed fabric deformation features identified by the preferred concentration and orientation of elongated mica particles (Figure 5e,f). These fabric features resemble the galaxy micro-deformation structures described by Karkanas (2019). Based on the inclined geometry, unsorted sediment, the preferential concentration of coarse clasts and the presence of vesicles and galaxy structures, we interpret MU J3-1 as a relatively fluid debris flow (Karkanas & Goldberg, 2018). The pre-existing inclined surface of LU J4 could provide the necessary angle for the development of a debris flow. Additionally, slumped laminated clasts (Figure 5c) imply that a certain level of steepness and topographic variation most probably also characterised the geometry of sediments deeper into the cave.

MU J2-1 has a similar groundmass with MU J3-1, but appears more sorted and with different proportions of coarse components. In comparison with MU J3-1, MU J2-1 also contains charcoal fragments and has a more granular microstructure. Overall, the micromass of MU J3-1 appears to be more phosphatic and isotropic in XPL. In places, the phosphatisation is accompanied by de-calcification, judging from the absence of a crystallitic b-fabric and the removal of calcite in altered limestone clasts. However, in contrast to this decalcified matrix, we observed many calcitic–crystallitic aggregates as well as bone fragments heavily cemented by calcite (Figure 5d). The considerable variation in postdepositional processes (decalcified vs. calcified components) in the same deposit is a strong indication that MU J3-1 represents a mixture of different sediment sources.

MU J1-1 is a moderately sorted deposit with sand-sized charcoal and bone fragments that comprises the uppermost part of the sequence, corresponding to LU J1 and modern cave use. It has a similar fabric to MU J2-1. The granular microstructure at the top part of LU J1 and the high frequency of channel voids demonstrate extensive bioturbation.

3.2 | Qyzyljartas

The Qyzyljartas cave is located at the north-eastern foothills of the Greater Qaratau range, about 10 km south-west of the Sozaq town. It is formed at the top of a steep sandstone outcrop (Figure 15c), while the feature itself has three openings, two of which join together to create a long, funnel-like cave, open at two sides. Two sloped passageways are oriented southwest and south (see also Figure S2c).

3.2.1 | Stratigraphic overview

Our investigations focused on the southwest passageway, where we excavated Test-pit E1 (1.5 × 1.5 m, 85 cm deep) at the top of the slope, near the upper opening, and Test-pit E2 (2 x 1 m, 1.5 m deep) at the bottom of the slope, near the opening at the face of the cliff. We exposed bedrock only in test-pit E2. The recorded sequences share common lithostratigraphic attributes and are generally correlated

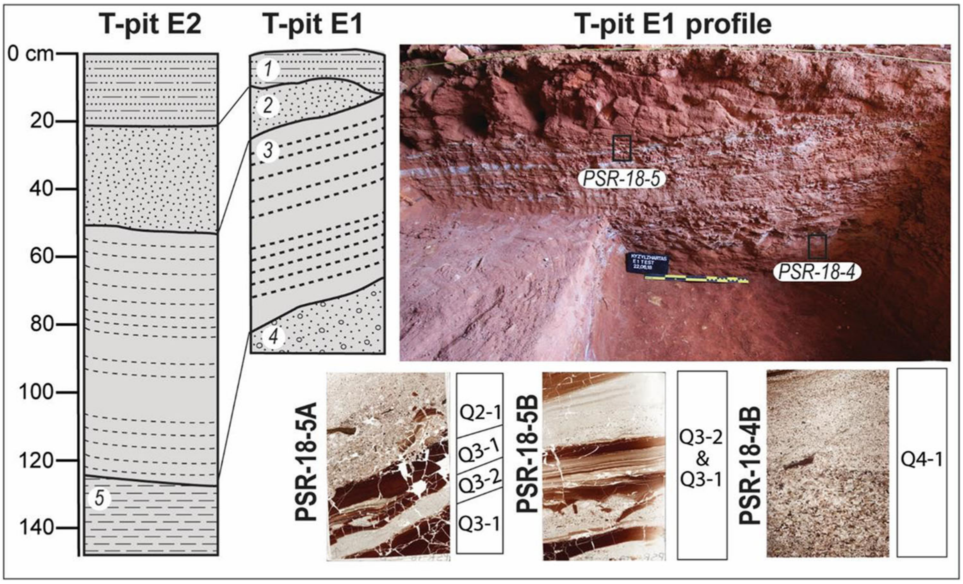

FIGURE 6 Stratigraphy and micromorphology in Qyzyljartas cave. Circled numbers indicate lithostratigraphic units: (LU Q1) sandy silt loam; (LU Q2) sandy loam; (LU Q3) pseudogleyed interbedded silty/clayey beds; (LU Q4) loamy sand; and (LU Q5) compacted clay. Black frames show the locations of micromorphological samples accompanied by a scan of the thin section in PPL and MU classification. LU 3 is also comprised of characteristic sandy and clayey interbedded deposits that are classified as MU types Q3-1 and Q3-2, respectively [Color figure can be viewed at wileyonlinelibrary.com]

(Figure 6). Only the lowermost units from each test-pit (LU Q4 and LU Q5) are not in a direct stratigraphic association, most probably due to the confined excavation area. Despite this difference, all layers dip towards the south following the inclination of the modern cave surface and have a homogeneous red to reddish-brown appearance. Based on structure, LUs alternate between loose clast-supported deposits dominated by fine sand-sized gravels and compacted matrix-supported deposits with a massive clay texture. LU Q3 differentiates from the rest of the sequence as it includes greyish-blueish redox-depleted horizons formed by settling of water (pseudogleying). An erosional contact characterises the transition from LU Q3 to LU Q2. Overall, the exposed stratigraphic sequence is entirely composed of geogenic components, with the complete absence of biogenic materials, such as bone. A single lithic artefact (chert flake) of indeterminate industry was also recovered during section cleaning of test-pit E1, but its stratigraphic location is unknown.

Qyzyljartas cave rests about 20 m above the modern river floor, indicating that the fluvial sequence found in the cave was probably deposited under an older episode of valley formation. This would suggest relatively old dates for the Qyzyljartas sequence, probably within the Late Pleistocene. A sample for OSL dating was collected from LU Q2, but the dating results are pending. Despite the minimal archaeology, the sequence at Qyzyljartas demonstrates a distinct case study for the impact of past fluvial dynamics for the development of pseudokarstic features in semiarid Kazakhstan (see also Iovita et al., 2020, p. 123).

3.2.2 | Micromorphology

MU Q2-1 is a clast-supported and poorly sorted deposit, primarily composed of rounded quartz (Figure 7a). Sandstone and organic shale rock fragments are common and are probably the source of the high quartz and organic-rich content observed under the thin section. The presence of large-sized and rounded coarse material demonstrates high-energy water action and long transport distances. Additionally, the inclusion of rip-up clasts that have the same clayey fabric as the underlying unit (MU Q3-1) demonstrates that water action also resulted in the erosion of adjacent sediments (Figure 7a).

The interbedded layers that constitute LU Q3 can be classified into two main MU types. MU type Q3-1 consists of matrix-supported reddish to dark reddish silty clay layers with high organic content and massive structure (Figure 7b). MU type Q3-2 are clast-supported layers consisting of abundant quartz grains and are generally devoid of clay (Figure 7b). Except for quartz, MU type Q3-2 includes rip-up clasts of MU type Q3-1, indicating that their deposition involved the erosion of the underlying surface. They show either a normal or reverse grading, and they are generally thicker than MU type Q3-1. Slight changes in sedimentation patterns resulted in interlaminations and variation in grain sizes in both MU Q3-1 and Q3-2 types. MU Q4-1 corresponds to the upper part of LU Q4 excavated in test-pit E1. The coarse material is dominated by coarse and sub-rounded quartz grains and demonstrates normal grading (Figure 6, thin-section scan PSR-18-4B). It consists of similar fabric units as MU Q2-1, but has higher abundance of interstitial clay.

3.3 | Ushozen 1

Ushozen 1 is a cave located ca. 10 km northwest of the Babaiqorgan village, Turkestan region, on the eastern bank of the homonymous Ushozen river. It is formed on Lower Devonian carbonates of the Aman formation at the northwestern part of the Greater Qaratau. The cave is composed of a single chamber, approximately 7 × 8 m (see also Figure S2d).

3.3.1 | Stratigraphy overview

Our test trench at Ushozen 1 reached a maximum depth of ~60 cm, exposing scarce Holocene archaeological material at the top of the sequence, but no dense cultural deposits. More specifically, Bronze Age ceramic sherds and bladelet lithic artefacts found in LU U1 and LU U2 demonstrate that the majority of the cave sediments were deposited during the Late Holocene. The LUs have a sandy silt

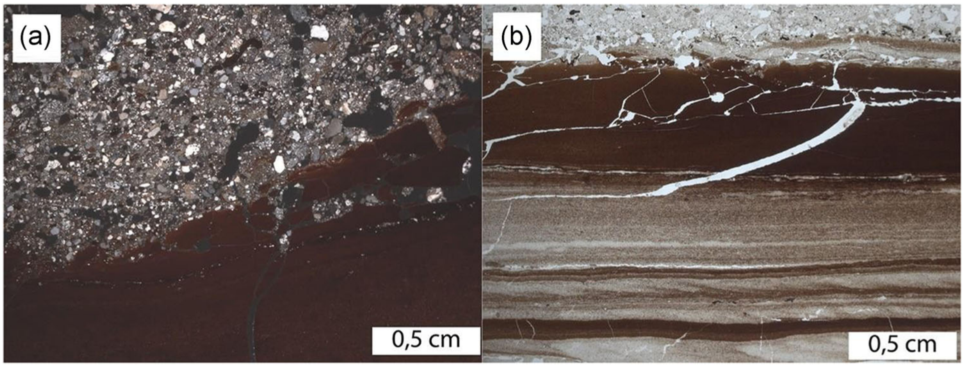

FIGURE 7 Microphotographs from Qyzyljartas. (a) Sharp and probably erosional boundary between the microstratigraphic unit (MU) Q2-1 and MU Q3-1; XPL. (b) Interbedded MU type Q3-1 (silty clay) and Q3-2 (sand) layers; PPL [Color figure can be viewed at wileyonlinelibrary.com]

texture, which becomes progressively more clayey and compacted towards the bedrock. The frequency of coarse clasts is generally low, except for LU U3, where abundant manganese oxide concretions and crusts were recorded directly above the bedrock. We hypothesise that these features have formed as nodules in the parent rock and that they are not pedogenic. Overall, textural attributes suggest that the settling of windblown material plays a major role in the accumulation of sediment in this cave.

3.3.2 | Micromorphology

Micromorphology sample PSR-18-6 was collected from the Eastern section of the test trench (PSR-18-6) covering the contact between LUs U2 and U3 (Figure 8). MU U2 and MU U3 show a bimodal distribution comprised mainly of coarse manganese oxide nodules, silty clay clasts associated with reworked endokarstic sediments (e.g., Goldberg et al., 2015, p. 623) and rock fragments in a finer loess-dominated matrix (Figure 9a). MU U3 has a more closely packed texture in comparison to MU U2 and is more bioturbated (Figure 9b,c). In contrast to MU U3, MU U2 also contains rounded soil aggregates that are sometimes phosphatised (compare Figure 9d with Figure 14b) and randomly distributed dung spherulites probably associated with degraded dung deposits. The homogeneous loess matrix in both MUs demonstrates that continuous aeolian processes play a major role in the accumulation of sediment in this cave. The soil aggregates were most probably transported to the cave by anthropogenic activity (e.g., Goldberg et al., 2009), since the absence of upslope soil cover excludes the possibility of colluvial input. Nevertheless, the phosphatised soil aggregates provide a proxy of prior burial and remobilisation in the cave environment, indicating some degree of reworking in the overall 'primary' loess matrix.

3.4 | Aqtogai 1

The Aqtogai 1 cave lies on the right bank of the Shabaqty river, about 10 km southeast of the Janatas town, Jambyl region, at the eastern part of the Lesser Qaratau (see also Figure S2e). It is formed on Middle Ordovician limestone, at an uplifted and highly deformed mountain front bounded by the Greater Qaratau Fault structure (Allen et al., 2001, p. 89).

3.4.1 | Stratigraphy overview

In Aqtogai 1, we expanded a test trench (3 × 2 m) partially excavated by Shunkov et al. (2018) at the back of the cave exposing a stratigraphic sequence of about 2.5 m without reaching the bedrock (Figure 10). The cultural material that we recovered from the cave so far is of Holocene age, based on the presence of pottery, and was retrieved only from the upper part of the sequence. However, our micromorphological analysis (see below) showed that dung pellets are also common in LU A7, indicating that the lower parts of the sequence are also most probably of Holocene age. Penetrometer tests at the base of our test-pit demonstrated at least 1 m of additional unexcavated sediments, suggesting the potential existence of Pleistocene deposits. The excavated deposits dip uniformly towards the entrance of the cave, but vary significantly in the abundance of coarse clasts. The lower half of the sequence is generally more clast-supported, with randomly distributed limestone

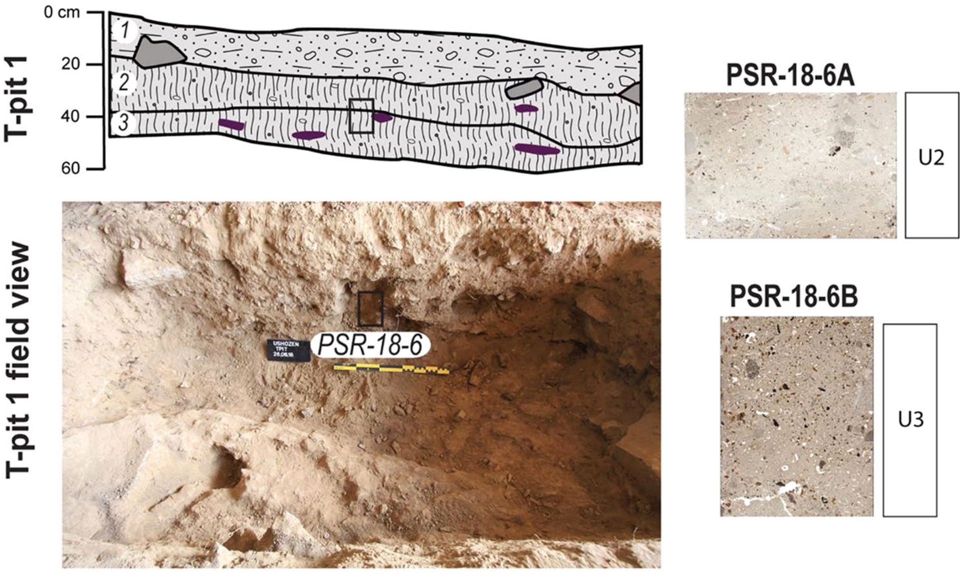

FIGURE 8 Stratigraphy and micromorphology in Ushozen 1 cave. Circled numbers indicate lithostratigraphic units: (LU U1) sandy loam; (LU U2) sandy silt loam; and (LU U3) sandy clay loam. Black frames show the locations of micromorphological samples accompanied by a scan of the thin section (in PPL) and MU classification [Color figure can be viewed at wileyonlinelibrary.com]

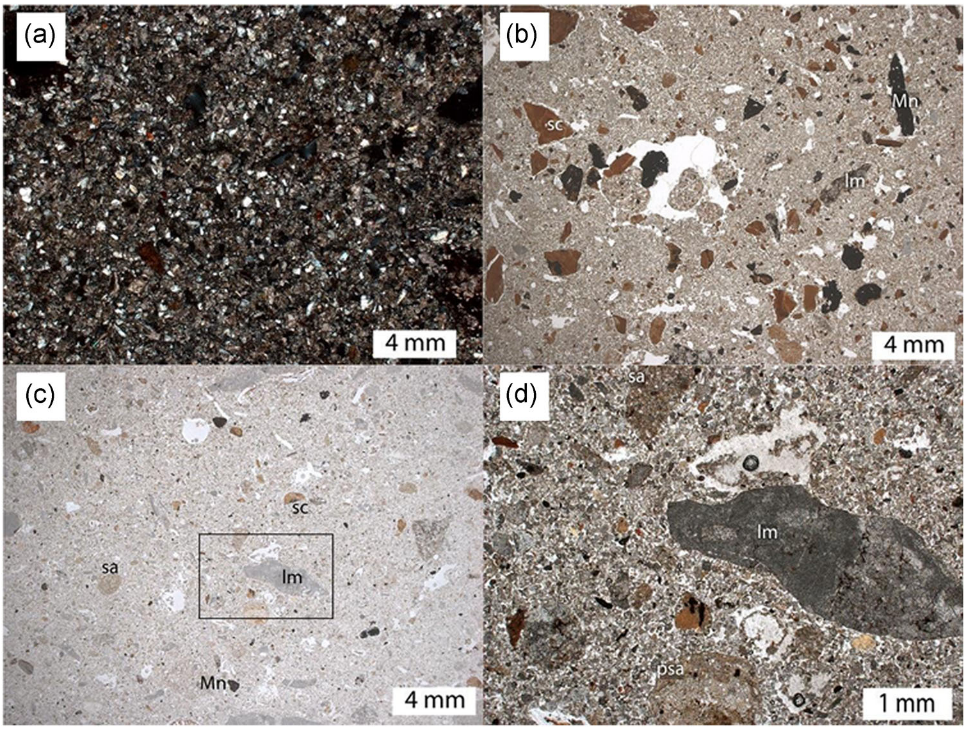

FIGURE 9 Microphotographs from Ushozen 1 cave. (a) Both MUs are comprised of randomly distributed, moderately to well-sorted quartz and mica grains in a calcitic–crystallitic micromass. This fabric is indicative of loess deposits; XPL. (b) MU U3; closely packed texture dominated by sand-sized silty clay clasts and manganese oxide nodules; PPL. (c) MU U2; lower abundance of coarse aggregates and smaller grain size result in a more open texture; PPL. (d) Higher magnification picture from the area corresponding to the black frame in (c). The presence of sand-sized rounded soil aggregates, some of which are phosphatised (see also Figure 14b), demonstrates variability in postdepositional phosphatisation; PPL. Abbreviations used in the microphotographs: limestone clast (lm), silty clay clasts (sc), manganese oxide (Mn), soil aggregate (sa) and phosphatised soil aggregate (psa) [Color figure can be viewed at wileyonlinelibrary.com]

fragments. In contrast, the upper part of the sequence is associated with matrix-supported layers that include calcite and clay nodules, and scarce limestone clasts. The topmost deposits (grouped as LU A1) consist of organic-rich and humified layers interbedded with ash lenses, resembling fumier/stabling deposits (Brönnimann et al., 2017; Macphail et al., 2004; Shahack-Gross, 2017). Our field observations largely agree with the stratigraphic descriptions provided by Shunkov et al. (2018).

3.4.2 | Micromorphology

Micromorphology sample PSR-19-6 is classified into two MUs (A6 and A7) corresponding to the contact between LUs A6 and A7. Both MUs are clast-supported and consist of autogenic geogenic materials with significant dung input (Figure 11a). MU 7 has a higher abundance of oriented coarse components, suggesting the operation of colluvial processes. Dung in both MUs demonstrates different stages of preservation based on the presence of complete dung pellets, humified dung aggregates and phosphatised material still preserving a few dung spherulites. The mixing of material in different states of preservation constitutes a proxy of sediment mixing.

The contact between LUs A4 and A5 is represented by MUs A4 and A5 recorded in micromorphology sample PSR-19-7. MU A5 has an open structure and includes gravel-sized dung pellets (Figure 11b). MU A4 (Figure 11c,d) shows a high abundance of charcoal, dung, authigenic gypsum and organics, demonstrating similarities to fumier/stabling deposits (Brönnimann et al., 2017; Macphail et al., 2004; Shahack-Gross, 2017). The presence of reworked geogenic cave materials (silty clay clasts, brecciated deposits), anthropogenic deposits and soil aggregates demonstrates that different sediment sources influenced the formation of MU A4.

MU A3 is a heterogeneous organic-rich deposit corresponding to LU A3. It consists of numerous rock fragments, phosphatic grains, endokarstic silty clay clasts and dung pellets (Figures 11e and 14c). Dung shows a varying degree of preservation like in MUs A6 and A7. The coarse material shows uniform dipping and orientation and is occasionally microlayered (Figure 11e). We hypothese that the preferential arrangement of coarse components and the microlayering are a result of colluvial processes due to the absence of well-defined microlaminated structures that could indicate water-lain deposition (in contrast see Jetiotau; Figure 5a,b and Qyzyljartas; Figure 7b).

MU A2 is the only matrix-supported deposit recorded microscopically. In comparison to the other deposits, it is characterised by

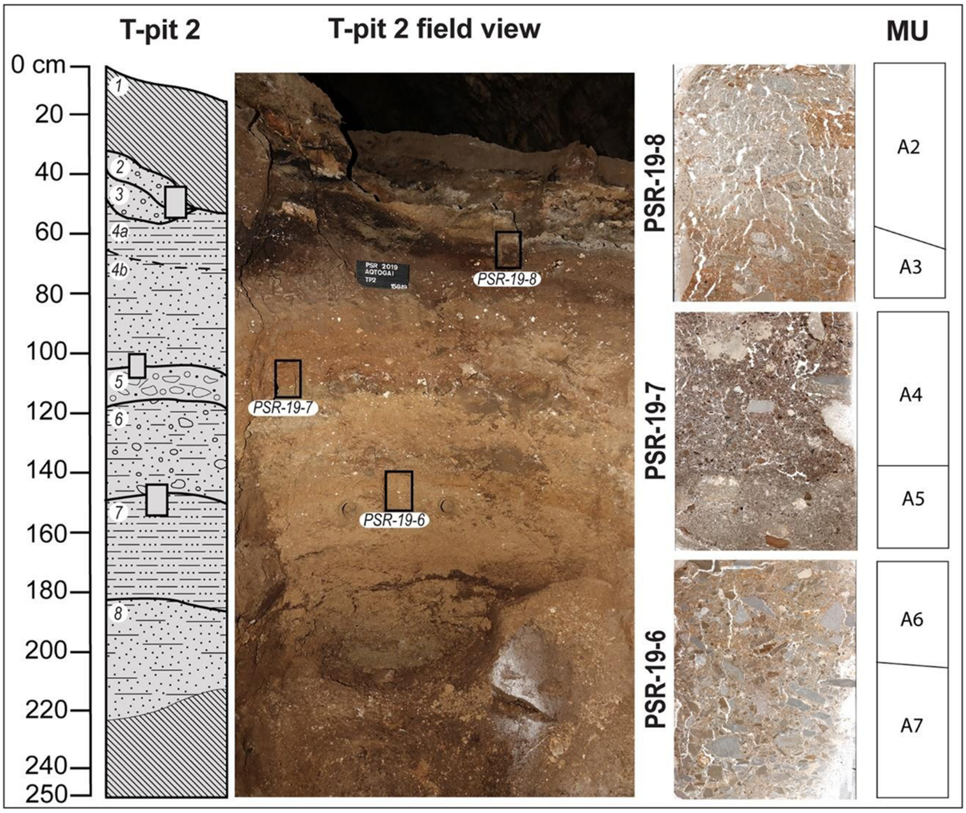

FIGURE 10 Stratigraphy and micromorphology in Aqtogai 1 cave. Circled numbers indicate lithostratigraphic units: (LU A1) heterogeneous sand and silt layers, disturbed; (LU A2) clay loam; (LU A3) clay loam; (LU A4a) sandy silt loam; (LU A4b) sandy clay; (LU A5) sandy silt loam; (LU A6) sandy silt loam; (LU A7) sandy clay; and (LU A8) sandy clay, slumped. Black frames show the locations of micromorphological samples accompanied by a scan of the thin section (in PPL) and MU classification [Color figure can be viewed at wileyonlinelibrary.com]

an abrupt lithological change, as it has a higher silt to very fine sand-sized quartz and mica component, indicating increased aeolian sedimentation. It also has a higher abundance of exotic schist rock fragments, most probably trampled into the cave by animal/human movement. Organic matter is predominantly distributed in the form of discrete laminations (Figure 11f). Aeolian accumulation and the presence of organic laminations indicate a slow net rate of deposition and the preservation of original sedimentary structures.

3.5 | Qaraungir 1

Qaraungir 1 cave is located in the foothills of the Lesser Qaratau range, 30 km northeast of Shymkent in southern Kazakhstan. The inner part of the cave has been previously excavated by Taimagambetov and Nokhrina (1998), with the oldest deposits dated to the Neolithic (see also Figure S2b).

3.5.1 | Stratigraphy overview

Building upon the work of Taimagambetov and Nokhrina (1998), who documented Neolithic occupation in the interior of the cave, we decided to excavate outside of the dripline to assess the lateral distribution of archaeological deposits. Our test trench at Qaraungir 1 reached a maximum depth of ~140 cm, exposing scarce Holocene archaeological material throughout the sequence, but no dense cultural layers (Figure 12). Therefore, the work of Taimagambetov and Nokhrina (1998) and our investigations suggest that the sediments inside and outside of the dripline in Qaraungir 1 were most probably deposited during the Holocene. The LUs have a silty clay to clayey loam texture, with a high frequency of coarse clasts especially in LU QA3 and towards the bottom of the trench. The shallow stratigraphy and the absence of cultural layers contrast with the thick cultural sequences recorded inside the cave by Taimagambetov and Nokhrina (1998). Therefore, Qaraungir 1 is the only surveyed cave where we have enough data to explore spatially diverse formation processes. Additionally, Qaraungir 1 is one of the few caves located in a down-slope position, providing an opportunity to study processes that may not be active in caves located in areas of higher topographic relief. Pending OSL dates will demonstrate when the sediments were deposited in the slope of Qaraungir 1.

3.5.2 | Micromorphology

MU QA3 and QA2 are both clast-supported deposits that consist of various geogenic and biogenic components (Figure 13). Although

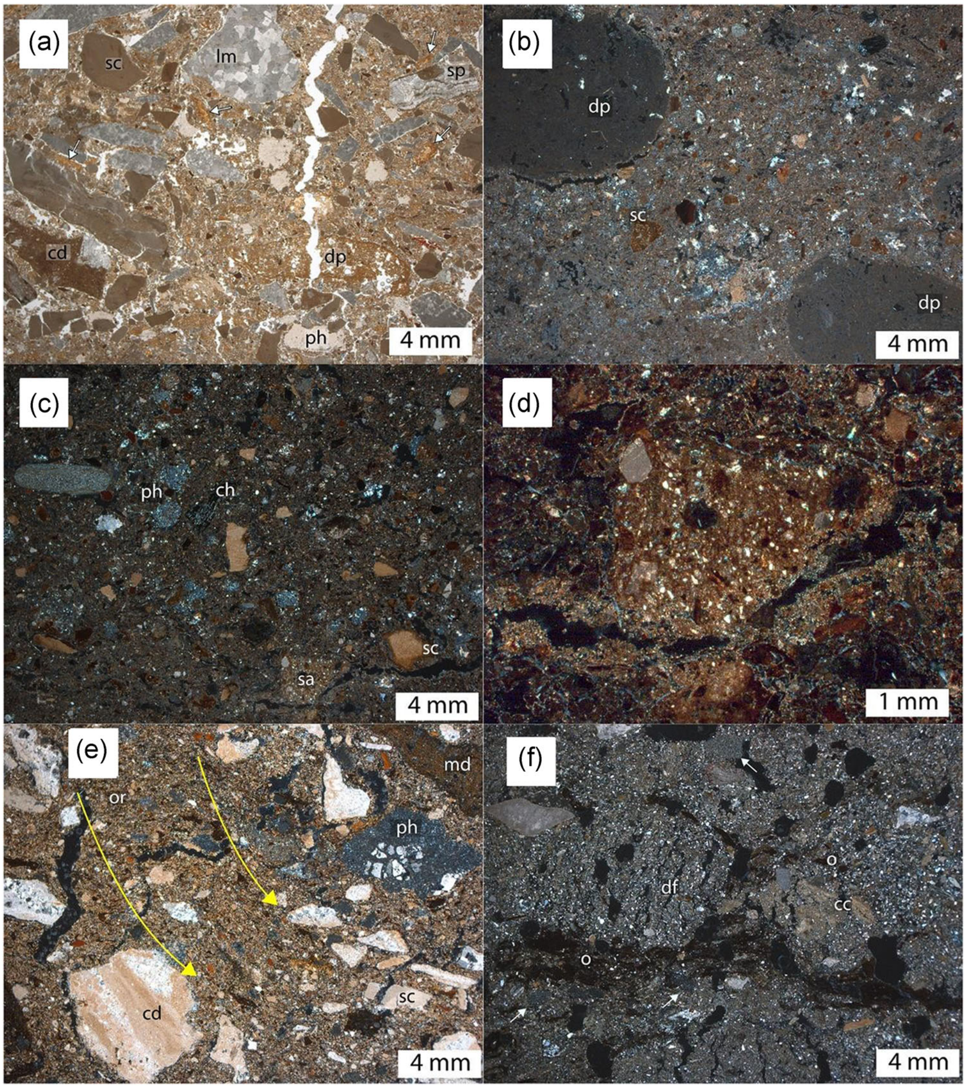

FIGURE 11 Microphotographs from Aqtogai 1 cave. (a) MU A7; randomly distributed coarse-sized limestone fragments (lm) and silty clay clasts (sc) mixed with dung pellets (dp), degraded dung (arrows) and phosphatised material (ph). Cemented deposits (cd) and a speleothem fragment (sp) are also present, indicating the mixing of heterogeneous deposits; PPL. (b) MU A5; gravel-sized dung pellets (dp) and few silty clay clasts (sc) embedded in an ashy matrix; XPL. (c) MU A4; gravel-sized and comminuted charcoal (ch), sediment aggregates (sa) and common isotropic phosphatic aggregates (ph); XPL. (d) Microphotograph of the soilaggregate indicated in (c). Note the high concentration of quartz silt and sand in the aggregate in comparison to the surrounding groundmass; XPL. (e) MU A3; Limestone fragments, cemented deposits (cd) and silty clay clasts (sc) mixed with phosphatic aggregates (ph) and massive dung (md) remains in an organic rich (or) matrix. Coarse material is preferentially distributed and oriented along planes (yellow arrows); XPL. (f) MU A2; calcitic–crystallitic aggregates (cc) and phosphatised (white arrows) aggregates mixed with decalcified matrix (df). Notice organic laminations (o) in different parts of the deposits; XPL [Color figure can be viewed at wileyonlinelibrary.com]

Qaraungir 1 is located in a downslope position, we did not observe significant soil input. The micromass fraction in both samples consists of silt-sized quartz, mica and calcite, indicating an aeolian source. Coarse clasts in both MUs are dipping down, following the inclination of the slope (Figure 13a). Mobilisation of cave material downslope is also evident by the presence of fabric hypocoatings around the coarse grains (Figure 13b). The development of phosphatic rinds around limestone clasts and the presence of grains of phosphatised sediments confirm that this material was originally deposited in the cave (Figure 14d). Despite the downslope movement, differences in the sorting of coarse material in MU QA3 indicate the preservation of microlayering. The deposits at Qaraungir 1 are exceptional examples of colluvially reworked loess-like cave sediments and provide evidence for the presence of active erosional processes in Qaratau caves.

4 | DISCUSSION

Our survey and micromorphological data suggest that the accumulation and preservation of sediments vary among the Qaratau caves. Below, we present a discussion of the processes that influence the

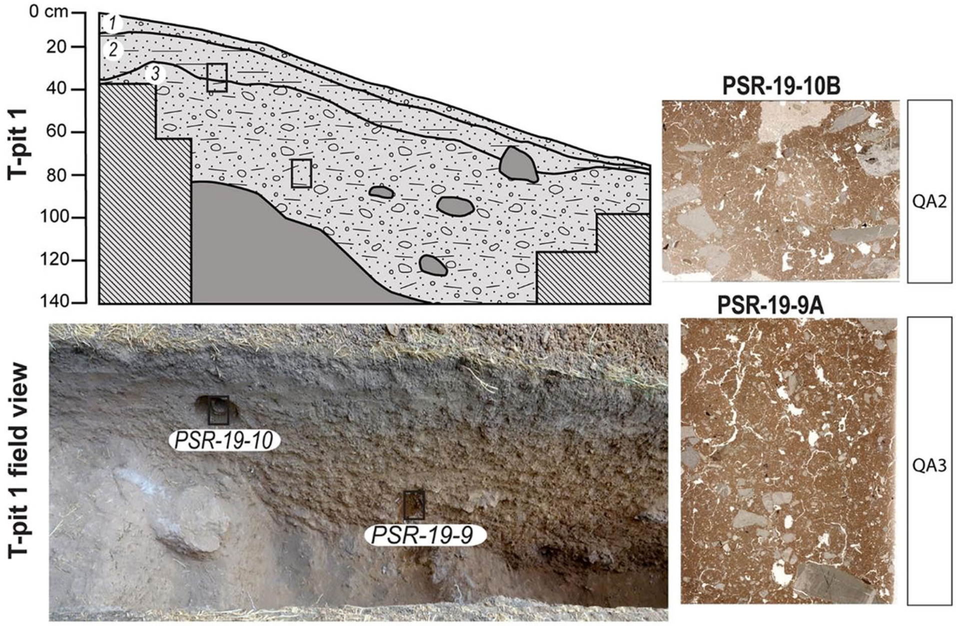

FIGURE 12 Stratigraphy and micromorphology in Qaraungir 1 cave. Circled numbers indicate lithostratigraphic units: LU QA1) sandy loam; LU QA2) sandy silt loam; and LU QA3) sandy clay loam. Black frames show the locations of micromorphological samples accompanied by a scan of the thin section (in PPL) and MU classification [Color figure can be viewed at wileyonlinelibrary.com]

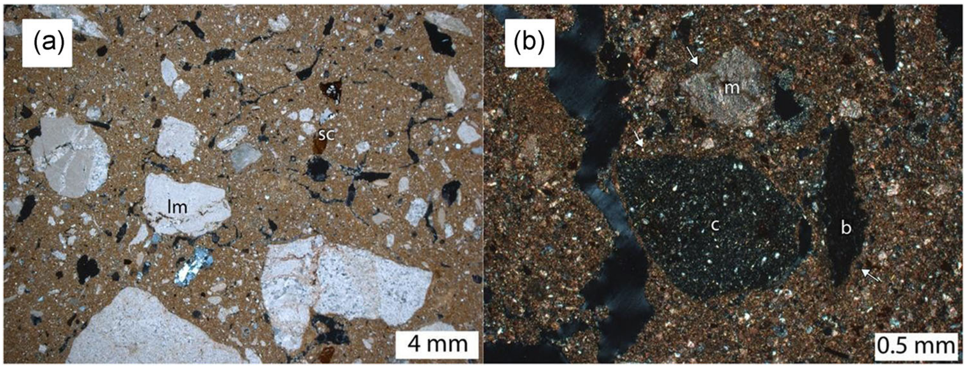

FIGURE 13 Microphotographs from Qaraungir 1 cave. (a) MU QA3; A comparison of the grain size and sorting between coarse components (e.g., limestone [lm] or silty clay [sc] clasts) between the lower left and the top right part of the microphotograph constitutes an example of microlayering; XPL. (b) MU QA2. Closer view of the calcitic–crystallitic b-fabric, rich in quartz and mica, that characterises the groundmass of both samples. Fabric hypocoatings (white arrows) around coarse clasts demonstrate reorientation of fabric by mechanical forces (Stoops, 2003, p. 112); XPL (see also Figure S3a for PPL version). Abbreviations used in the microphotograph: phosphatised grain (ph), marble (m) and bone (b) [Color figure can be viewed at wileyonlinelibrary.com]

distribution of cave sediments in respect to the regional semiarid context.

4.1 | Summary of site formation processes in the Qaratau caves

Aeolian input leads to the formation of loess-like cave sediments that share common macroscopic characteristics across the cave sites. These sediments can be identified in the field based on pale colour, silty texture and massive structure (see also Krajcarz et al., 2016). Based on our micromorphology analysis, we assume that these textural attributes result from similarities in the micromass, which is characterised by the high abundance of very fine sand to silt-sized quartz, mica grains and calcite. However, under the microscope, loess-like cave sediments also demonstrate a high degree of compositional variability, as they mix with a wide range of materials depending on the cave environment. Therefore, homogeneous wind-blown loess deposits were not observed in any of the caves, suggesting that the loess-like material found within the caves was likely reworked through a number of different processes.

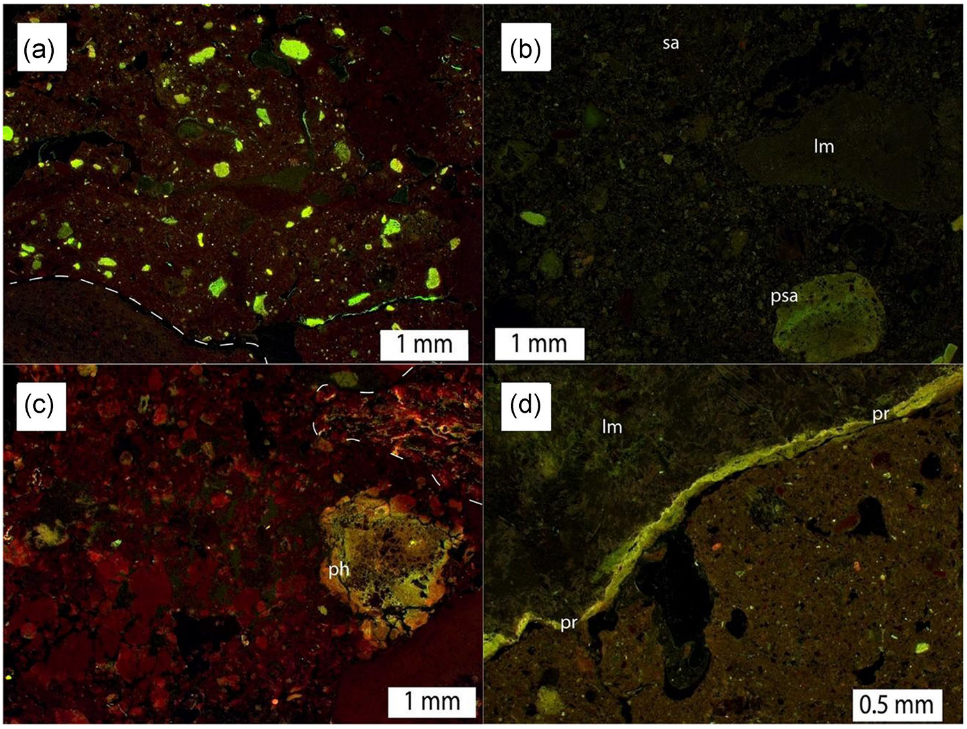

FIGURE 14 Cave deposits seen under the fluorescent microscope. (a) Jetiotau, MU J3-1. Mixed organic matrix rich in sand-sized phosphatic aggregates contrasting with laminated silty clay inclusions of endokarstic origin (white dashed line). (b) Ushozen, MU U2. Similar field of view as Figure 9d. Soil aggregates (sa) and limestone clasts (lm) mixed with isolated phosphatised soil aggregate (psa) in an organic-poor deposit. (c) Aqtogai 1, MU A3. Organic-dominated matrix with phosphatic grains (ph) and dung pellets (white dashed line). (d) Qaraungir 1, MU QA2. Phosphatic rind (pr) around limestone (lm) in an organic-rich matrix. See also Figure S3b,c for PPL and XPL microphotographs [Color figure can be viewed at wileyonlinelibrary.com]

In general, the loess-like cave sediments that we observed diverge from the typical loess deposits recorded in the region. Loess along the Kazakh Tian Shan piedmont is dominated by the remobilised silt of alluvial fans and plains, while the low content of sand-sized grains indicates that distal sources such as deserts and dunes have a minor impact on loess formation (Li et al., 2020). This implies that local topography and proximity to sources significantly influence loess accumulation, since an important proportion of loess originates from proximal sources and topsoils (Li et al., 2018; Sprafke et al., 2018; but also Crouvi et al., 2010). In comparison to the Tian Shan catchment, the Qaratau mountains are flanked by the deserts of the Qyzylqum and the Moyunqum, which could act as sources of short-distance sand transport under strong wind regimes. Based on this assumption, we hypothesise that the proximity of the Qaratau caves to sandy deserts could consequently explain the presence of the fine sand quartz and mica identified in most of our sediment samples. In this regard, we expect a bimodal distribution of loess depending on variations of wind strength or the distance of the caves from the source area, with coarser loess deposits in caves located closer to the sandy deserts. Further sedimentary analyses from cave and local desert loess samples will test if proximity to deserts influences the source and grain size of cave deposits. Additionally, animal and human trampling or transport of plant material (Butzer, 1982, p. 80; Goldberg et al., 2009) could have transported soil aggregates with fine sand quartz into the caves (see Aqtogai 1, Ushozen 1). Overall, a combination of mainly geogenic and potentially anthropogenic processes results in loess-like cave sediments with a sandier and more polymodal distribution than the silt-dominated piedmont loess deposits.

In contrast to grain shape, in this study, we demonstrated that grain orientation constitutes an especially useful tool for identifying postdepositional processes of loess-like cave sediments. Under the microscope, uniformly oriented mica particles may constitute a proxy of water reworking, or even form deformation features in a mass movement context. However, due to the homogeneity of the loess matrix, low-energy reworking cannot always be observed in the micromass. Therefore, we suggest that the distribution and depositional history of the coarser sand-sized material that becomes mixed with loess is usually more helpful in documenting reworking in loess-like cave sediments.

Based on our survey results, the majority of the examined caves are hydrologically abandoned in the sense that they are decoupled from any major groundwater input (Sherwood & Goldberg, 2001). As a consequence, their morphology indicates dry conditions and a stable microenvironment, which implies that sediments deposited in those contexts are largely unaltered by large-scale reworking processes induced by active groundwater flow. While this may be true on a larger scale, our micromorphological analysis demonstrated that water action also impacted the development of cave sediments in the past. First, we recorded lithified silty clay clasts that are associated with the karstic phase of cave formation. These resistant old karst deposits remobilise throughout the sequence and constitute an important component of some cave deposits (Aqtogai 1, Jetiotau, Ushozen 1). Additionally, unlithified laminations of fine material (see Aqtogai 1) or channel deposits of coarse sand (see Qyzyljartas) demonstrate more recent water-driven processes. In this context, the frequent occurrence of low-energy colluvial (Qaraungir 1, Aqtogai 1) or higher-energy mass movement processes (Jetiotau) near the cave entrance also requires some degree of water saturation (Karkanas & Goldberg, 2018). We hypothesise that regional orographic precipitation supplies the necessary water content driving the depositional processes described above, which may occasionally trigger a reactivation of the karst network. Because of higher relief, the Qaratau mountains and the greater Tian Shan mountain range are characterised by higher mean annual precipitation values and more frequent precipitation extreme events in comparison to other regions of Central Asia (Ma et al., 2020).

The depositional processes outlined above have diverse implications for the preservation of cave sequences. First of all, the thick aeolian deposits demonstrate that there are extensive periods of time where stable conditions without groundwater flow enabled the settling of loess into the caves. Cave surfaces must have been exposed for a significant amount of time based also on the high content of phosphatised and calcified material (Barbieri et al., 2018; Miller, 2015). Except from phosphatisation, diagenetic processes are mainly linked to the formation of authigenic gypsum in Aqtogai 1, indicating mostly dry conditions. The absence of intensive diagenetic processes demonstrates that the Qaratau caves show good potential for the preservation of organic materials. In this regard, the case study from Aqtogai 1 demonstrates that the high frequency of organic materials is of high importance for the build-up of thick cave sequences.

4.2 | Investigating cave erosion by combining field survey and micromorphology

Sherwood and Goldberg (2001) suggested that postdepositional alteration of cave sediments is site-specific, as it is controlled by microenvironmental factors such as bedrock characteristics, landscape location, local hydrology and human activity. Despite site variation, our field survey and micromorphology work in the Qaratau mountains revealed that regional patterns of sediment preservation and reworking may be inferred.

Understanding the processes that accumulate or remove cave sediments in Kazakhstan is a major challenge since most of the surveyed caves and rockshelters did not contain any sediments. In this regard, field survey provided minimum evidence for the erosion of sediments in individual caves. Potentially older cave surfaces, identified by the presence of remnant flowstone crusts, were recorded only in a handful of caves (Figure 15a). The limited occurrence and spatial extent of flowstone surfaces, in parallel with the complete absence of sediment pockets, provide no evidence for the presence of remnant deposits and cave floors in the surveyed features. In addition, evidence for ongoing sediment erosion is also minimal. Active erosional processes were recorded only in Nazugum rockshelter (Iovita et al., 2020), where we documented water channels washing out parts of the sequence (Figure 15b).

Generally, traces of erosion are more frequently related to processes affecting the exterior of karst features. In Qaratau, semiarid conditions hinder the development of thick soils, facilitating the formation of scree-mantled slopes and talus cones (Abrahams et al., 1994). Based on the high frequency of these erosional landforms in the mountain foothills of the surveyed areas, we hypothesise that caves or cave sediments might have been eroded from the landscape. In this context, the caves and rockshelters that we surveyed are usually found in a mid-slope position (Cuthbertson et al., 2021), overlooking these erosional scree slopes (e.g., Figure 15c). The relative absence of karst features at the bottoms of slopes and valley systems may imply the erosion of pre-existing features or their masking by accumulated scree and loess. Furthermore, larger-scale erosion has sometimes also been observed in the front part of the caves, triggered by breaks in the local topography (e.g., Figure 15d). Finally, structural indications such as the association of caves with fault-lines and the frequent occurrence of large-size rockfall in their interior (Iovita et al., 2020) indicate that caves in Qaratau are also influenced by active tectonics.

Overall, our field survey observations suggest that erosion of cave sediments in Kazakhstan seems to operate differently between the level of the site and the level of the landscape. On the site scale, cave environments seem to be relatively stable without a complex history of remnant flowstone surfaces, cemented deposits and erosive water action. High-intensity water-induced processes such as channel erosion or cementation are more common in more humid and tropical climates (e.g., O'Connor et al., 2017) and appear to have less impact on the evolution of cave deposits in drier regions like Kazakhstan. However, on the landscape scale, our observations suggest that cave and rockshelter erosion in Kazakhstan is controlled by broader changes tied to landscape stability and the semiarid geomorphological processes that form scree-mantled slopes.

Even though it is difficult to test if the caves that are now empty had sediment at some point in the past, some implications regarding the erosion of cave sediments have been provided by our micromorphological analysis. Erosion and redeposition of older deposits have been documented in the micromorphology samples from all the examined caves, suggesting that reworking of cave sediments is a common theme in the Qaratau mountains. High-intensity processes such as mudflows or sheetflows usually remobilise older sediments and materials within the caves, forming indicative microstructures. The reworking of individual grains along different parts of the cave sequences, such as the endokarstic silty clay clasts recorded in Ushozen 1, indicates constant but lower-intensity processes that do not produce specific microstructures. Moreover, the redeposition of cave materials from the interior of Qaraungir 1

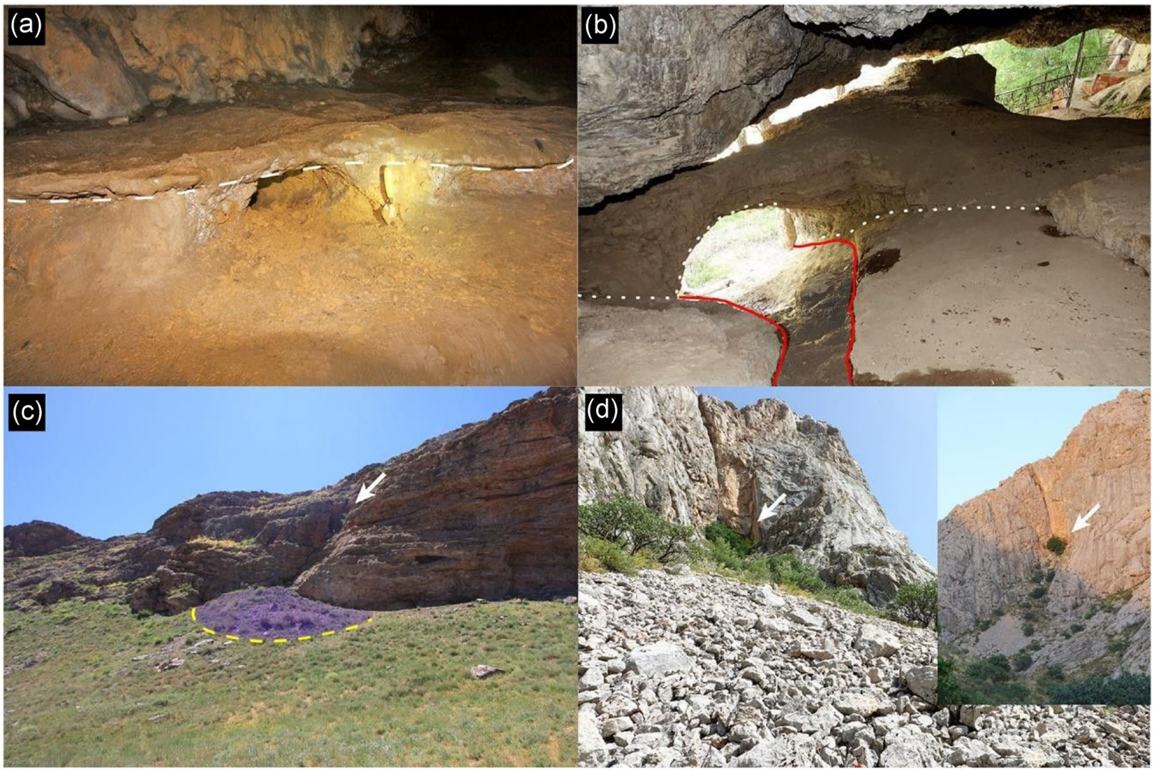

FIGURE 15 Erosional processes in the interior and exterior of caves and rockshelters in our study region. Isolated examples of eroded sediments in the interior of caves. (a) Potentially truncated flowstone surface and underlying clay sediments (contact marked with white dashed line) in Jetiotau cave. (b) Erosional processes triggered by water action in Nazugum rockshelter. Water channel (red solid line) cutting through sediments (white dotted line). Note the presence of an erosional arch. The absence of sediments at the back of the feature contrary to the front indicate large-scale erosion. (c) Talus cones (here opaquely masked and outlined by a yellow dashed line) in proximity to cave entrances (marked with white arrow) provide implications for near-entrance structural collapse. Qyzyljartas cave. (d) Tuttybulaq 2 (white arrow) provides an example of features located at a mid-slope elevation overlooking rock mantled slopes. Right; distant landscape view. Left; close-up of the moderately sorted scree leading to the cave [Color figure can be viewed at wileyonlinelibrary.com]

towards the slope outside of the dripline is an indication that colluvial processes also influence the preservation of deposits in the few caves that are associated with soil-mantled slopes.

Overall, the scarcity of Pleistocene sediments in contrast to the more common Holocene sediments (Iovita et al., 2020) could indicate that erosional processes affecting cave deposits were more intense during the Pleistocene. Even though this study demonstrated some potential pathways of cave erosion in specific sites, at this stage, we cannot provide a more detailed chronological framework for the onset of erosional processes for the whole range of the Qaratau mountains. Future work in prospective sites and their corresponding catchments will address the probability, intensity and chronology of erosion.

4.3 | The Qaratau caves in the context of Central Asian Palaeolithic and semiarid zones

Our survey in the Qaratau mountains has significant implications for the formation of the archaeological cave record in Central Asia (see also Iovita et al., 2020). Despite the numerous caves that we recorded during our survey, only a few contain thick sediment sequences. A similar situation seems to occur in Uzbekistan and neighbouring Mongolia, where recent surveys recorded only a few cave sites (Nishiaki et al., 2018, 2019; Vanwezer et al., 2021). The formation of cave sites requires human activity and a geomorphological setting that promotes the accumulation and preservation of sediments (Mentzer, 2017). The geological structure is important for the preservation of sediments, and cave sites formed in rock strata that slope downwards tend to be eroded away under long time scales (Heydari, 2007). Besides rock type and structure, climate is the other major influence on the type of sediments deposited in a landscape and the pathways of its subsequent erosion (Bull, 2009; Burbank & Pinter, 1999; Ke & Zhang, 2021). However, the impact of climate on the evolution of cave sediments has been contextualised only for some environments in the geoarchaeological literature, such as Mediterranean and tropical (Morley, 2017; Woodward & Goldberg, 2001). Central Asia and other arid or semiarid settings have been largely neglected in the discussion of cave-formation processes, probably due to the lack of a group of well-documented sites. In this regard, exploring the formation processes of caves in semiarid regions is particularly important for geoarchaeological research for two main reasons. First, arid and semiarid regions that were traditionally considered as barriers of human movement now seem to have functioned as corridors of dispersal under more favourable climatic conditions (Breeze et al., 2016; Li et al., 2019; Osborne et al., 2008). By understanding the factors that govern the deposition and erosion of long cave sequences in these arid regions, we can assess preservation probability and better plan future surveys. Second, formation processes encountered in semiarid climates, such as increased loess deposition, could be expected in cave sequences in other parts of the world where conditions were more arid in the past, for instance, during glacial stages (Barbieri et al., 2018; Krajcarz et al., 2016). In this context, understanding the formation of loess-like cave sediments is especially important since archaeological caves with loess or generally aeolian deposits have a global distribution. Moreover, in areas like Kazakhstan, where well-developed speleothem records are absent and loess has a substantial distribution, loess in caves could constitute both a palaeoenvironmental archive (e.g., Pirson et al., 2006) and a chronostratigraphic tool for correlating caves sites, loess open-air sites and geological deposits. A micromorphological approach, as provided in this study, can distinguish between primary and secondary loess and therefore provide a depositional context for palaeoenvironmental proxies.

An allochthonous sediment source is important for the filling of caves with sediment (Iovita et al., 2020), and in Kazakhstan, aeolian loess supplies the dominant proportion of allochthonous sediment accumulation. However, loess deposition is not uniform and is influenced by various parameters such as altitude, topography and wind direction (Y. Li et al., 2015, 2020). The variability in the distribution of aeolian loess sediments, together with the erosional processes presented in this study, could potentially explain the frequency of empty caves in Qaratau mountains. The limited soil cover in semiarid areas (e.g., Figure 15c,d) also hinders the redeposition of soil material in the caves through colluvial processes. This type of allochthonous colluvial sediment is important for the build-up of cave sequences in slightly more humid climates, such as dry-Mediterranean (Frumkin et al., 2016; Woodward & Goldberg, 2001). Nevertheless, the alteration of hot and cool conditions that are also present in semiarid areas facilitates the thermostatic weathering of the bedrock and leads to the accumulation of angular limestone debris in cave sequences (Cremaschi et al., 2015). Roof spall and remobilised karstic sediments constitute the dominant autochthonous geogenic deposit that we recorded in our survey. In the case of pseudokarstic caves, such as Qyzyljartas, the disintegration of non-carbonate bedrock into loose sediment will provide an extra source of autochthonous sediment accumulation (see also Iovita et al., 2020). These autochthonous deposits mix with the aeolian component by colluvial and mass movement processes triggered inside the cave environment. Other processes, such as spring activity and sheetflow processes, have only been recorded at Obi-Rakhmat (Mallol et al., 2009), and we hypothesise that they are relatively rare in Central Asian and semiarid caves, since we also recorded them only in rare instances (e.g., Qyzyljartas and Nazugum).

The alteration of aeolian deposition and geogenic colluvial reworking seems to be a recurring pattern not only in caves of the semiarid part of Central Asia (this study and Sel'ungur; Krivoshapkin et al., 2020) but also in the caves from the boreal and more humid Altai region. Available data from Strashnaya (Krivoshapkin et al., 2018, 2019), Chagyrskaya (Derevianko et al., 2018) and Ust'-Kanskaya (Lesage et al., 2020) suggest that some cave sequences in the Altai are punctuated by the accumulation of loess-like sediments and autochthonous colluvial reworking. However, Altai caves are also often characterised by cryogenic deformation features, most probably induced by the more boreal and humid local climatic conditions (Derevianko et al., 2018; Krivoshapkin et al., 2019; Morley, 2017). These features are postdepositional and constitute an additional agent of sediment mixing. In contrast, cryoturbation features have not yet been reported in the more arid southern Central Asia, which could imply less intense postdepositional processes and more secure cave contexts.

Despite the more intense postdepositional processes, the Altai region has a much higher frequency of Palaeolithic cave sites in comparison to Central Asia. If we adopt a 'simplistic' climatic approach to the data, we could argue that the distribution of cave sites reflects solely different climatic conditions. According to this approach, the Altai cluster reflects a more diachronic occupation favoured by the overall better climatic conditions, while semiarid Central Asia functions only as a corridor that witnesses substantial occupation only during phases of ameliorating climate. This approach, however, would not be valid based on the recent modelling data that suggest the presence and movement of hominin groups in the IAMC during both glacial and interglacial conditions (Glantz et al., 2018; Li et al., 2019). While the reasons for this preferential distribution of cave sites remain unclear, we believe that they also reflect variations in the processes that influence the formation of cave sediments and the stability of caves on the landscape. More evidence on regional site formation processes would greatly enhance the challenging task of correlating site distribution with human choice and dispersal routes.

4.4 | Methodological implications

In this study, we demonstrated that micromorphological analysis could provide valuable information in archaeological surveys. By collecting qualitative data from several sites, we answered questions that often remain unaddressed by survey projects that focus primarily on the quantitative distribution of sites on the landscape. The occurrence and thickness of sediment cover, the origin of cave deposits, depositional processes and postdepositional alterations are key site-specific parameters that could not have been explored using a purely landscape approach. Incorporating this information together allows us to examine the dominant processes that control the formation of the record but also demonstrates the degree of variation within a specific region. In the Qaratau example, we have demonstrated that even though loess is the main driver of allochthonous sediment accumulation, the way it gets reworked among the different caves varies greatly. In this regard, formation processes are not only influenced by site location but also by the site-specific depositional history. Other processes, such as anthropogenic input (e.g., at Aqtogai 1), or rare depositional processes (e.g., at Qyzyljartas) could form cave sequences that stand out from the rest of the data set. Moreover, by combining macroscopic observations for the whole data set together with site-specific analysis, we were able to address how representative our interpretations are in a broader sense. In this way, we supply the reader with data that are often omitted in archaeological survey publications. Even for sites of low archaeological potential, our micromorphological survey approach enables us to reconstruct cave life histories and model the potential formation processes that characterise our study area (see also Karkanas et al., 2021) and also to potentially examine factors of human absence in the landscape as well as presence.

5 | CONCLUSIONS

This study provides a preliminary geoarchaeological context for our ongoing cave survey in the Qaratau mountains of South Kazakhstan (Iovita et al., 2020). By combining model-led intensive field survey (Cuthbertson et al., 2021) with micromorphological analysis, we assessed the distribution of cave sediments and prominent caves on the landscape and demonstrated how cave-formation processes are tied to the regional geomorphological and climatic factors. This study has implications for caves in similar semiarid settings and provides a methodology for contextualising survey data with a high-resolution analytical framework. Thus, it addresses themes that often remain unaddressed in the (geo) archaeological literature since well-documented semiarid caves sites are lacking, fieldwork projects often do not carry out high-resolution site-specific analyses and micromorphology studies often do not utilise a regional approach by focusing on a group of different cave sites.

Qaratau caves recorded different depositional styles, but loess-like cave deposits and reworking processes of varying intensity dominate the sediment sequences. Moreover, the depositional and erosional processes that characterise the surveyed caves are also associated with their landscape location. We hypothesise that hillslope erosion might influence the removal of caves from the landscape, and in combination with loess cover, might blanket caves found downslope.

Overall, a new Denisova-type cave has not yet been found during our survey in the Qaratau mountains. Caves with the potential for Pleistocene sediments were inferred only from a couple of sites, and future excavation and dating are required to resolve the sedimentary record of these caves. To date, only two Palaeolithic cave sites are known from Kazakhstan, even though the number of Palaeolithic open-air sites is gradually increasing (Anoikin et al., 2019; Ozherelyev et al., 2019). However, the low frequency of Palaeolithic cave sites is a general characteristic of the caves found in the semi-arid regions of Central Asia and contrasts with the high clustering of Palaeolithic cave sites found in the more humid northern fringes of the Altai. This distribution cannot be explained only by climatic factors, and in this paper, we present some of the formation processes that influence the deposition and erosion of sediments in Central Asia. We hypothesise that additional geological factors such as the distribution and type of karst landscapes, together with the subsistence strategies used by hominin groups in semiarid environments, shape the complex Central Asian Palaeolithic record. A methodology focusing on survey and high-resolution analysis, similar to the one used in this study, has the potential to unravel this record and provide the necessary data for further modelling research targeting human dispersals in the region.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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Supplementary material

Cave site	Country/Region	References
Byka cave complex	Russia; Altai	Derevianko et al. (1998); Zwyns, (2012, p. 300)
Chagyrskaya	Russia; Altai	Derevianko et al. (2013); Derevianko et al. (2018)
Denisova	Russia; Altai	Kuzmin & Orlova (1998); Derevianko et al. (2005); Douka et al. (2019)
Iskra cave	Russia; Altai	Derevianko et al. (1995); Markin & Antipov, 2012
Kaminnaya	Russia; Altai	Derevianko et al. (1998); Markin (2019)
Maloyalomanskaya	Russia; Altai	Derevianko & Petrin (1989); Goebel (2004, p. 173); Zwyns (2012, p. 292)
Okladnikov	Russia; Altai	Derevianko, Markin, & Shunkov (2013)
Strashnaya	Russia; Altai	Krivoshapkin et al. (2018)
Ust'-Kanskaya	Russia; Altai	Rudenko (1961); Kuzmin & Orlova (1998); Lesage et al. (2020)
Obi-Rakhmat	Uzbekistan Western Tian Shan	Krivoshapkin et al. (2007); Asmerom et al. (2018)
Amir-Temir	Uzbekistan Alay Mountains Baisun-Tau Range	Okladnikov (1940); Movius (1953); Vishnyatsky (1999); Nishiaki et al. (2018)
Aman-Kutan (?)	Uzbekistan Alay Mountains Zeravshan Range	Movius (1953); Ranov & Davis (1979); Vishnyatsky (1999)
Anghilak	Uzbekistan Alay Mountains Zeravshan Range	Glantz et al. (2003); Glantz et al. (2008)
Teshik-Tash 1	Uzbekistan Alay Mountains Zeravshan Range	Okladnikov (1940); Movius (1953); Vishnyatsky (1999); Nishiaki et al. (2018)
Ushbas	Kazakhstan Qaratau Mountains	Alpysbaev (1961); Grigoriev & Volkov (1998)
Peshchera	Kazakhstan Bukhtarma Reservoir	Gokhman (1957)
Ogzi-Kichik	Tajikistan	Ranov & Davis (1979)
Selungur	Kyrgyzstan Fergana Valley	Krivoshapkin et al. (2020)

Table S1. Known Paleolithic cave sites in Central Asia.

Name	Feature type	Sediment thickness	Region
Aqbastau 1	Cave	-	Qaratau
Aqbastau 2	Cave	-	Qaratau
Aqbastau 3	Cave	-	Qaratau
Aqmeshit cave	Cave	Significant	Qaratau
Aqtogai 1	Cave	Significant	Qaratau
Aqtogai 2	Cave	-	Qaratau
Aqtogai 3	Cave	-	Qaratau
Aquiyq 1	Cave	-	Qaratau
Aquiyq 2	Cave	Moderate	Qaratau
Besaryq 1	Cave	-	Qaratau
Boraldai 1	Rockshelter	Moderate	Qaratau
Boraldai 2	Cave	-	Qaratau
Boraldai 3	Cave	-	Qaratau
Bostau	Cave	-	Qaratau
Eltai	Cave	-	Qaratau
Hantagi 1	Cave	Significant	Qaratau
Hantagy 2	Rockshelter	-	Qaratau
Iqansu 2	Cave	-	Qaratau
Iqansu 3	Cave	-	Qaratau
Iqansu 4	Cave	-	Qaratau
Janibek cave	Cave	Minor	Qaratau
Jaryqbas 11	Cave	-	Qaratau
Jaryqbas 6	Cave	-	Qaratau
Jaryqbas 7	Cave	-	Qaratau
Jaryqbas 8	Cave	-	Qaratau
Jaryqbas 9	Cave	-	Qaratau
Jetiotau cave	Cave	Significant	Qaratau
Kishi Boraldai 1	Cave	-	Qaratau
Kishi Boraldai 2	Cave	-	Qaratau
Kishi Boraldai 3	Cave	-	Qaratau
Kishi Boraldai 4	Rockshelter	-	Qaratau
Kishi Boraldai 5	Cave	-	Qaratau
Marsel Ungiri	Cave	Minor	Qaratau
Mashat	Rockshelter	-	Qaratau
Mayatas	Cave	Moderate	Qaratau
Qaqpaq	Cave	Minor	Qaratau
Qaragashty	Vertical cave	Moderate	Qaratau
Qaraungir 1	Cave	Significant	Qaratau
Qaraungir 2	Cave	-	Qaratau
Qaraungir 3	Cave	Minor	Qaratau
Qaraungir Iqansu	Cave	-	Qaratau
Qatyn Qamal	Cave	Moderate	Qaratau
Qumyra	Cave	-	Qaratau
Qundyz	Cave	-	Qaratau
Qyzqorgan 1	Cave	-	Qaratau
Qyzqorgan 2	Cave	-	Qaratau
Qyzqorgan 3	Rockshelter	-	Qaratau
Qyzqorgan 4	Rockshelter	-	Qaratau
Qyzqorgan 5	Rockshelter	-	Qaratau
Qyzyljartas	Cave	Significant	Qaratau

Sairamsu 1	Cave	-	Qaratau
Sairamsu 2	Cave	-	Qaratau
Saryaigyr	Cave	-	Qaratau
Shabaqty	Cave	-	Qaratau
Shaqpaq	Cave	Moderate	Qaratau
Sholsai	Rockshelter	-	Qaratau
Shuqyrshaq 1	Rockshelter	?	Qaratau
Suly Cave	Cave	-	Qaratau
Taldybulaq 1	Cave	Significant	Qaratau
Taldybulaq 2	Cave	-	Qaratau
Taldybulaq 3	Cave	-	Qaratau
Taldybulaq Aqsu	Cave	-	Qaratau
Temir 1	Cave	-	Qaratau
Temir 2	Cave	Significant	Qaratau
Tereksai 3	Cave	-	Qaratau
Terekti	Cave	-	Qaratau
Tesiktobe	Cave	-	Qaratau
Tura cave	Cave	-	Qaratau
Turmys 1	Cave	Moderate	Qaratau
Turmys 2	Cave	-	Qaratau
Turmys 3	Cave	-	Qaratau
Tuttybulaq 1	Cave	Significant	Qaratau
Tuttybulaq 2	Cave	Significant	Qaratau
Uiyq	Cave	-	Qaratau
Ushbas 1	Cave	Significant	Qaratau
Ushozen 1	Cave	Moderate	Qaratau
Ushozen 3	Rockshelter	-	Qaratau
Yntaly 3	Cave	Significant	Qaratau
Yntaly 4	Rockshelter	Moderate	Qaratau
Aqtasty 1	Cave	-	Tian Shan/Jungarian Alatau
Aqtasty 3	Cave	Moderate	Tian Shan/Jungarian Alatau
Aqtasty 4	Cave	-	Tian Shan/Jungarian Alatau
Aqtasty 5	Cave	-	Tian Shan/Jungarian Alatau
Arasan	Cave	-	Tian Shan/Jungarian Alatau
Black cave	Rockshelter	-	Tian Shan/Jungarian Alatau
Jetiungir	Cave	-	Tian Shan/Jungarian Alatau
Kokpek 1	Cave	-	Tian Shan/Jungarian Alatau
Meshel Qora	Cave	-	Tian Shan/Jungarian Alatau
Nazugum	Rockshelter	Significant	Tian Shan/Jungarian Alatau
Qorjynbai	Cave	-	Tian Shan/Jungarian Alatau
Qyryqungir	Cave	Significant	Tian Shan/Jungarian Alatau
Ungirsai	Cave	-	Tian Shan/Jungarian Alatau
Alybai 1	Rockshelter	-	Kazakh Altai
Alybai 4	Rockshelter	-	Kazakh Altai
Novaya Bukhtarma Cave	Rockshelter	-	Kazakh Altai
Pantelejmonovka Grottoes	Rockshelter	-	Kazakh Altai

Table S2. Caves surveyed by the PALAEOSILKROAD project (PSR) during 2017-2019. Sediment thickness groups (Minor: <0.5 m; Moderate: >0.5 m; Significant: >2 m). For more information see the original text. Pleistocene sediments followed by (?) indicate potential chronology, since confirmation by absolute dating is pending. For the locations of the features see the supplementary material in Cuthbertson et al. (2021).

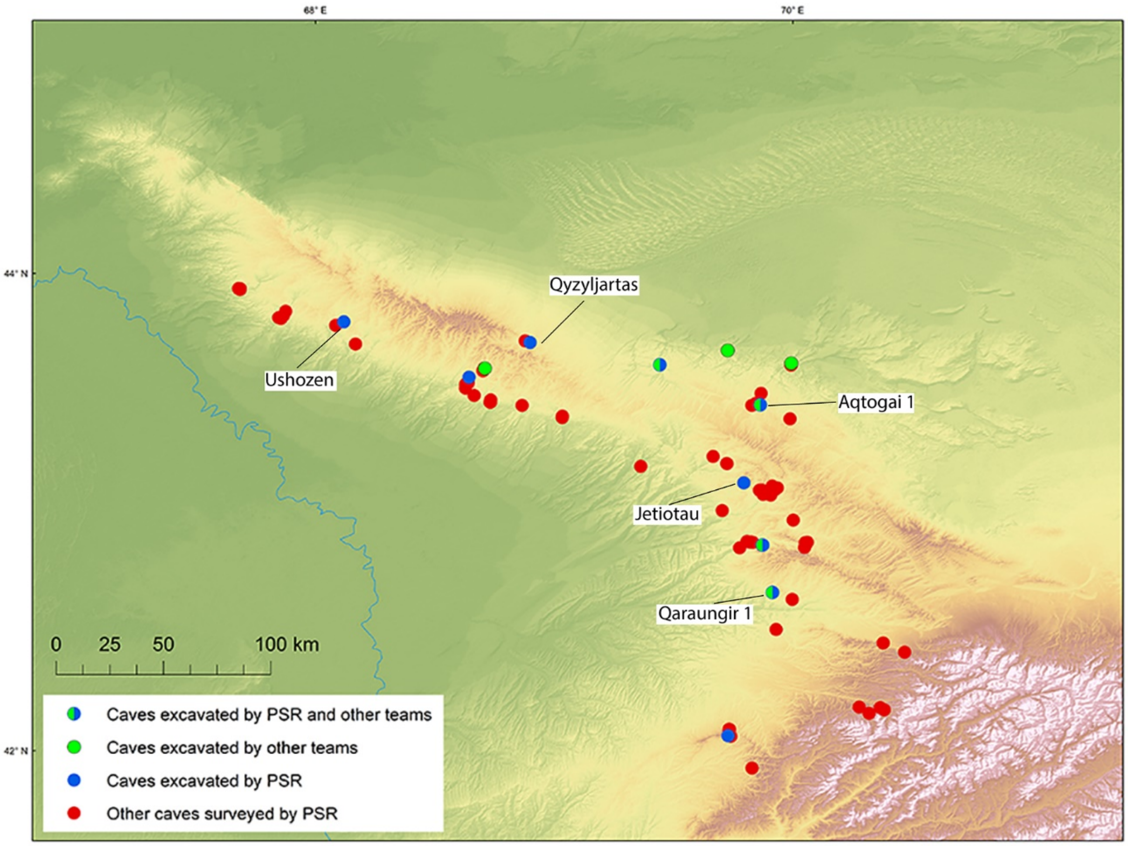

Figure S1. Surveyed caves in the Qaratau mountains with the name of the sites discussed in this study. Data sources: Global Administrative areas (GADM) (Hijmans, 2012), vector and raster map data from Natural Earth (www.naturalearthdata.com) and Shuttle Radar Topography Mission (SRTM) Version 4 (Jarvis et al., 2008)

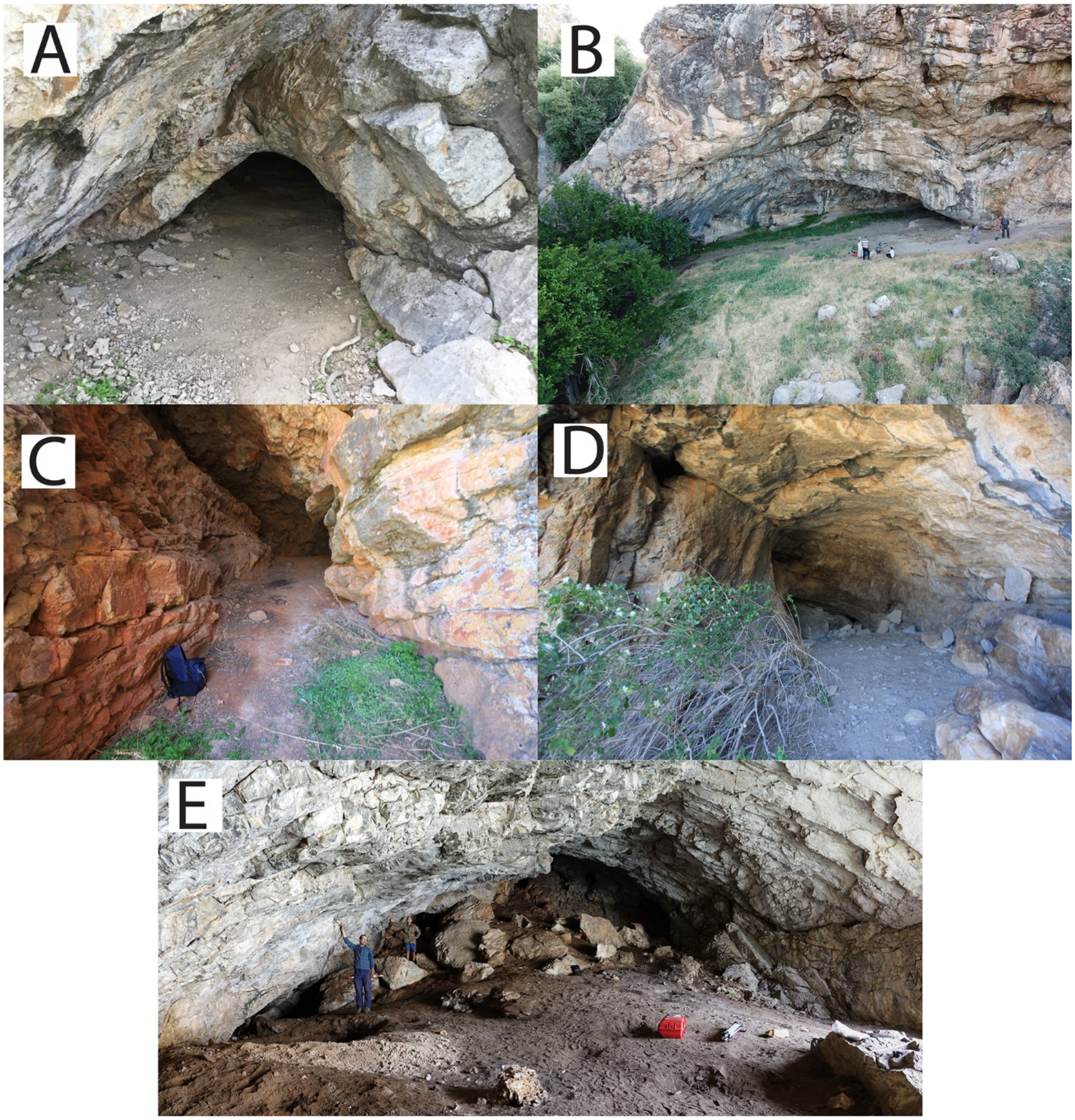

Figure S2. Interior of each of the caves analyzed in this study. A) Jetiotau. B) Qaraungir 1. C) Qyzyljartas. D) Ushozen 1. E) Aqtogai 1.

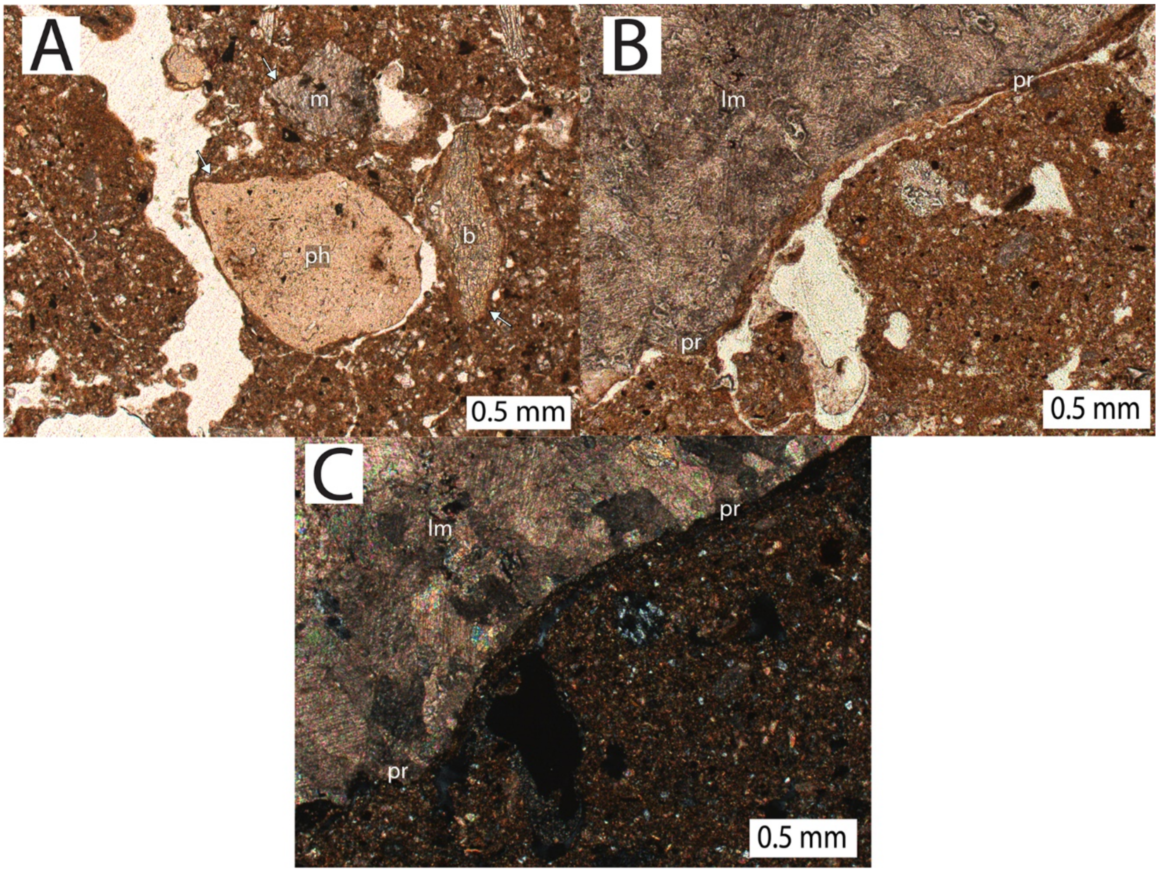

Figure S3. Microphotographs from Qaraungir 1. A) MU QA2, same as Fig. 13B; PPL. B) MU QA2, same as Fig. 14D; PPL. C) MU QA2, same as Fig. 14D; XPL. Pale yellow color in PPL and isotropic texture in XPL confirm the phosphatic nature of the limestone rind. Abbreviations used in the microphotographs: limestones (lm), phosphatized grain (ph), phosphatic rind (pr), marble (m), bone (b).

Site	Lithostratigraphic unit (LU)	Thickness (cm)	Munsell	Texture/Consistency	Boundary Form/ Distinctness	Inclusions (frequency/size)	Other characteristics
Jetiotau	LU J1	30-35	10YR 4/3 brown	Sandy loam/Friable	-	Limestone clasts (30%/2-5cm); bones (5%/2-4cm); charcoal (5%/3cm);	Bioturbation; granular structure
	LU J2	30	2.5Y 5/4 light olive brown	Silty clay loam/ Slightly firm	Wavy/Sharp	Limestone clasts (5%/2-4cm);	
	LU J3	40	10YR 5/4 yellowish brown	Clay loam/Friable	Wavy (?)/Abrupt	Limestone clasts (20%/ <10cm); bones (5%); charcoal (<2%)	
	LU J4	35-40	2.5Y 5/4 light olive brown	Silty clay loam/ Slightly firm	Wavy/Sharp	Limestone clasts (5-10%/5cm);	
	LU J5	65	10YR 5/3 brown	Clay loam/ Slightly Firm	Smooth/Clear	Limestone clasts (20-30%/2-7cm)	
Qyzyljhartas	LU Q1	10-20	5YR 4/6 light yellowish brown	Sandy loam/ Slightly firm	-	Gravels (5-10%/<2cm)	
	LU Q2	30	10 R 4/6 red	Loamy sand/Loose	Smooth/Abrupt	Gravels (10%/<1-3cm) In places yellowish-reddish clay chunks (5%, 1-3cm)	
	LU Q3	70-80	5G 7/1 light greenish gray 5G 7/2 pale green 10R 4/4 weak red	Different textures ranging from silty clay to sandy loam/Firm	Smooth/Abrupt with LU 2. Smooth/Sharp between sub-layers	In sandy loam layers: Gravels (20%/<2cm) Yellowish clay chunks (5%/1-5cm)	Interbedded redox depleted layers indicating periodic saturation
	LU Q4	15	10R 4/6 red	Loamy sand/Firm	Smooth/Sharp	Gravels (10%/<2cm)	Very similar to LU 2
	LU Q5	20-25	10R 4/8 red	Clay/Very Hard	Smooth/Clear	-	Massive structure
Ushozen 1	LU U1	~20	2.5Y 4/3 olive brown	Sandy loam/ loose	-	Gravels (10-15%/<10cm)	
	LU U2	~20	2.5Y 3/3 light olive brown	Sandy silt loam/ slightly firm	Smooth/clear		
	LU U3	10-15	10 YR 4/3 brown	Sandy clay loam/firm	Smooth/clear	Mn concretions (~30%/3-10 cm)	
Aqtogai 1	LU A1	~30-50	Sequence of organic-rich and humified layers with ash lenses. Heterogeneous textural attributes				Modern disturbances

	LU A2	~10-15	10 YR 4/3 brown	Clay loam/friable	Smooth/clear	Limestone fragments (~2%/1-4cm); charcoal (2%/mm-2cm); clay nodules (~2-5%/mm); whitish/orange, whitish calcite (?) nodules (5%/mm);	
	LU A3	~10-15	10 YR 2/2 very dark brown	Clay loam/friable	Smooth/clear	Whitish calcite (?) nodules (~30%/mm)	
	LU A4a	~20	10 YR 2/2 very dark brown	Sandy silt loam/friable	Smooth/clear	Whitish calcite (?) nodules (5-10%/1-3 cm); clay nodules (<5%/1-3cm)	
	Lu A4b	~30	7.5 YR 3/4 dark brown	Sandy clay/friable	Smooth/gradual	Whitish calcite (?) nodules (20%/3-4cm)	
	LU A5	~15					
	LU A6	~20-30	7.5 YR 5/6 strong brown	Sandy clay loam/friable	Smooth/abrupt	Limestone clasts (10-15%/mm-6cm); calcite nodules (5%/mm-cm)	
	LU A7	~25	7.5 YR 6/8 reddish yellow	Sandy clay/ slightly firm	Smooth/ clear		
	LU A8	~25	10 YR 6/3 pale brown	Sandy clay/firm	Undefined/abrupt	Limestone clasts (30%/ up to 8 cm)	Lower part is slumped
Qaraungir 1	LU QA1	~10	10 YR 4/3 brown	Sandy loam/friable	-		Bioturbation
	LU QA2	~20	10 YR 4/2 dark grayish brown	Silty clay loam/very firm	Smooth/clear	Gravels (5%/ 3-4cm)	
	LU QA3	~100	10 YR 5/4 yellowish brown	Clay loam/ slightly firm	Smooth/clear	Gravels (15-30%/ up to 10cm)	Sandier & with more clasts towards the bottom of the excavation

Table S3. Index of field stratigraphic descriptions for the caves presented in this study.

			Groundmass			
Site	Sample	Microunit (MU)	Coarse material	Micromass	C/f limit & relative distribution pattern	Other descriptive attributes
Jetiotau	PSR-18-2	**MU J4-1**	Micas (S-FS) Quartz (S-VFS)	Mixture of micrite and clay Calcitic crystallitic	C/f limit: 4µm Fine monic; open porphyric	Voids: pr, vs Pefofeatures: dusty clay coatings, pendents, crescent coatings impregnative Fe/Mn oxides Microstructure: laminated Fabric: mica grains are strongly oriented parallel to the inclined basal boundary of the MU Also: bioturbation
		MU J3-1	Laminated silty clay clasts (G, ❖) Limestone clasts (G, **) Micas (VFS-MS) Quartz (VFS) Feldspar (FS) Phosphatized grains (**) Coprolites (MS-VCS, **) Bones (MS-VCS, *) Quartz-rich breccia (MS, *) Organic-rich aggregates (MS, *) Siliceous clasts (FS, *)	Mixture of clay, calcite, quartz and mica Calcitic crystallitic. Stipple-speckled. Monostriated.	C/f limit: 20µm Single-spaced porphyric	Voids: vg, vs, ch Pedofeatures: dusty clay coatings, infillings and crescent coatings; impregnative Fe/Mn oxides; often granostriated b-fabric around coarse clasts Other biogenic inclusions: carnivore coprolites
		MU J2-1	Laminated silty clay clasts (MS-G, **) Limestone clasts (FS-G, **) Bones (FS-G, **) Charcoal fragments (S-VFS, *) Phosphatized grains (VFS, *) Eggshell (FS, *) Quartz (VFS) Mica (VFS)	Mixture of clay, calcite, quartz and mica Calcitic crystallitic	C/f limit: 20µm Open-spaced porphyric	Voids: ch, vs Pedofeatures: calcite coatings Also: calcite alteration

		MU J1-1	Limestone clasts (FS-G,❖) Bones (MS-G, **) Charcoal fragments (S-G, **) Phosphatized grains (VFS-MS, *) Laminated silty clay clasts (G, *) Quartz (VFS) Mica (VFS)	Mixture of clay, calcite, quartz and mica Calcitic crystallitic	C/f limit: 20µm Single-spaced porphyric	Voids: ch, vs Pedofeatures: calcite coatings; often granostriated b-fabric around coarse clasts. Also: calcite alteration
Qyzyljartas	PSR-18-5A	**MU Q2-1**	Quartz (FS-G, ❖) Sandstone fragments (MS-G, **) Shale fragments (MS-G, **) Organic matter (FS-MS, **) Schist fragments (MS, *)	Iron-rich clay Calcitic crystallitic	C/f limit: 4µm Close porphyric; Close fine enaulic	Voids: vs, cp Pedofeatures: impregnative Fe oxides; granostriated b-fabric around coarse clasts
	PSR-18-5B	**MU Q3-1**	Quartz (S-VFS) Mica (S-VFS)	Iron-rich clay	C/f limit: 4µm Fine monic	Microstructure: massive
	PSR-18-5B	**MU Q3-2**	Quartz (S-CS,◆) Mica (SFS, *) Sandstone fragments (MS-G, *) Schist fragments (MS-G,*) Rip-up clasts (MS-G, *) Organic matter (FS, *)	Mixture of quartz and mica Calcitic crystallitic	C/f limit: 20µm Coarse monic Close fine enaulic	Voids: cp Pedofeatures: impregnative Fe oxides Fabric: occasionally with normal or reversed grading

	PSR-18-4	**MU Q4**	Quartz (FS-CS, ❖) Organic matter (**) Sandstone fragments (MS-CS, *) Shale fragments (MS, *) Mudstone fragments (MS-VCS, **) Schist fragments (CS-VCS, *) Chert fragments (MS-VCS, **)	Iron-rich clay	C/f limit: 4µm Close fine enaulic	<u>Pedofeatures</u>: impregnative Fe oxides <u>Fabric</u>: grading upwards
Ushozen 1	PSR-18-6A	**MU U2**	Marble, limestone, siltstone fragments (MS-G, ❖) Silty clay clasts (FS-CS, **) Mn-oxide nodules (FS-CS, *) Soil aggregates (CS, *) Coprolites (CS, *) Bones (FS-CS, *) Shell (MS, *) Mica (VFS) Quartz (VFS)	Mixture of calcite, clay, quartz, mica, dung spherulites Calcitic crystallitic	C/f limit: 20µm Double-spaced porphyric	<u>Voids</u>: vs, ch <u>Pedofeatures</u>: calcite coatings. <u>Microstructure</u>: weakly developed platy microstructure at the lower part of thin section <u>Also</u>: calcite weathering-limestone alteration
	PSR-18-6B	**MU U3**	Mn oxide nodules (MS-CS, ❖) Silty clay clasts (VFS-CS, ❖) Marble, limestone fragments (MS-G, **) Bones (FS-VCS, *) Mica (S-VFS) Quartz (S-VFS)	Mixture of calcite, clay, quartz and mica Calcitic crystallitic	C/f limit: 20µm Single-spaced porphyric	<u>Voids</u>: vs, ch <u>Pedofeatures</u>: impregnative Mn oxides <u>Also</u>: localized burrowing
Aqtogai 1	PSR-19-6	**A7**	Limestone, siltstone, chert fragments (MS-G, ♦) Silty clay clasts (MS-G, ❖) Dung (❖) Phosphatized material (MS-VCS, **) Mica (S-VFS) Quartz (S-VFS) Hornblende: (S-VFS)	Mixture of clay, calcite, quartz, mica, dung spherulites and organics; Calitic crystallitic	C/f limit: 20µm Single-spaced porphyric	<u>Voids</u>: vs, ch <u>Pedofeatures</u>: fabric hypocoatings around coarse clasts; calcite coatings/infillings; gypsum infillings related to dung. <u>Dung</u>: different preservation states (complete pellets, humified, degraded)

PSR-19-6	**A6**	Limestone, chert, schist fragments (MS-G, ❖) Silty clay clasts (MS-G, ❖) Dung (**) Phosphatized material (MS-VCS, *) Mica (S-VFS) Quartz (S-VFS)	Mixture of clay, calcite, quartz, mica and organics Calcitic crystallitic	C/f limit: 20µm Close porphyric to single-spaced porphyric	Voids: vs, ch Pedofeatures: fabric hypocoatings around coarse clasts Dung: different preservation states (complete pellets, humified, degraded) Also: calcite alteration
PSR-19-7	**A5**	Limestone, siltstone fragments (CS-G, *) Dung pellets (G, ❖) Silty clay clasts (*, MS-VCS) Charcoal (FS, *) Soil aggregates (CS, *)	Mixture of clay and calcite Calcitic crystallitic	C/f limit: 20 µm Close fine enaulic	Voids: cp, ch Post-depositional: authighenic gypsum
PSR-19-7	**A4**	Breccia, limestone, siltstone, schist fragments (VFS-VCS, ❖) Phosphatized aggregates (CS-G, ❖) Silty clay clasts (MS-G, **) Dung aggregates (VFS-MS, **) Charcoal (FS-G, **) Soil aggregates (MS, *) Bone fragments (FS-CS, *) Mica (VFS) Quartz (VFS)	Mixture of clay, calcite, quartz and mica Calcitic crystallitic	C/f limit: 20µm Close fine enaulic	Voids: cp, ch Post-depositional: authighenic gypsum
PSR-19-8	**A3**	Rock clasts (♦) Phosphatized aggregates (MS-G, ❖) Silty clay clasts (MS-G, **) Dung pellets (G, **)	Mixture of clay, calcite, dung spherulites and organics Calcitic crystallitic	C/f limit: 20µm Single-spaced enaulic	Voids: cp, ch Fabric: show uniform orientation and inclination of rock clasts Also: calcite alteration, etching of limestones, dolomitization

	PSR-19-8	**A2**	Limestone, dolomite, schist, chert (❖) Phosphatized aggregates (MS-CS, *) Eggshell (VCS, *) Quartz (VFS-FS) Mica (VFS-FS) Hornblende (FS)	Micture of clay, calcite, quartz and mica Calcitic crystallitic	C/f limit: 20µm Close fine enaulic	<u>Voids</u>: cp, ch, vertical elongated voids produced by sampling
Qaraungir 1	PSR-19-10B	**QA 2**	Limestone, shale, chert clasts (MS-G, ❖) Bones (VCS, *) Shell (MS-CS, *) Coprolites (VCS, *) Charcoal (FS-VCS, *) Quartz (S-VFS) Mica (S-VFS)	Clay-rich with calcite, quartz and mica Calcitic-crystallitic	C/f limit: 20µm single spaced porphyric	<u>Voids</u>: vs, ch <u>Microstructure</u>: granular, in places <u>Pedofeatures</u>: Mn impregnative pedofeatures, Mn oxide nodules; fabric hypocoatings around coarse grains; calcite coatings <u>Also</u>: calcite alteration, phosphatic rinds around coarse clasts
	PSR-19-9A	**QA 3**	Limestone, shale, breccia clasts (FS-G, ❖) Coprolites (MS-CS, *) Bones (VCS-G, *) Eggshell (MS-G*) Shell (MS-CS, *) Quartz (S-VFS) Mica (S-VFS)	Clay-rich with calcite, quartz and mica Calcitic-crystallitic	C/f limit: 20µm Close porphyric	<u>Voids</u>: vs, ch <u>Pedofeatures</u>: Mn impregnative pedofeatures; fabric hypocoatings around coarse grains, calcite coatings <u>Also</u>: calcite alteration, phosphatic rinds around coarse clasts

Texture: S = Silt, VFS = Very Fine Sand, FS = Fine Sand, MS = Medium Sand, Coarse Sand=CS, Very Coarse Sand = VCS, G = Gravel;
Voids: pr = planar, vs = vesicles, vg = vughs, ch = channels, cp = complex packing voids;
Fabric unit abundance: very few (<5%), *, few (5-15%), **, common (15-30%), ❖, frequent (30-50%),♦ , Dominant (◆)

Table S4. Micromorphology descriptions for the presented thin sections following the nomenclature proposed by Stoops (2003)

This is the submitted version of the following manuscript: ***“Using formation processes to explore low-density sites and settlement patterns: a case-study from the Swabian Jura”****, which has been submitted for publication at the Journal of Palaeolithic Archaeology.*

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Using formation processes to explore low-density sites and settlement patterns: a case-study from the Swabian Jura

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Abstract:	Palaeolithic archaeologists often rely on cave and rockshelter sites with rich occupation levels to explore hominin behavior and settlement patterns. However, a closer look into regional occupation data may reveal an uneven distribution of sites and the presence of occupational hiatuses or low-density occupation horizons that often remain understudied. In contrast to this trend, this paper focuses on low-density occupation data to explore regional settlement patterns, using the rich and well-studied Palaeolithic record of the Swabian Jura, Germany, as a case study. In this regard, we employ a geoarchaeological approach based on micromorphology to investigate the formation processes of two low-density occupation sites, Schafstall II and Fetzershaldenhöhle, and compare their formation history with the geogenic sequence from Lindenhöhle. We demonstrate that the investigated sites have comparable formation processes, despite their differences in chronology and context. We argue that humans used Schafstall II and Fetzershaldenhöhle for short-term activities, while the sites mostly served as carnivore activity areas, emphasizing the importance of fauna in the accumulation of thick sedimentary sequences. In addition, our findings corroborate the regional climatic record and provide novel insights into the geomorphological history of the less studied Lauchert Valley, where Schafstall II is located. By comparing our results with data from intensively occupied caves in the Swabian Jura, we provide broader implications for the settlement patterns of Upper Palaeolithic hunter-gatherers. We conclude with a methodological framework for investigating sites in hunter-gatherer contexts combining a distributional and a site-specific approach.
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Suggested Reviewers:	Alvise Barbieri alv.barbieri@gmail.com Dr. Barbieri is a geoarchaeologist who specialized in micromorphology and therefore can review the technical aspects of the micromorphological approach used in this paper. He has also worked thoroughly in the Swabian Jura and contributed to the investigation of formation processes and human occupation in this region.
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	Lawrence Straus lstraus@unm.edu Dr. Straus has conducted extensive research on the settlement patterns of European Palaeolithic and the concept of occupational intensity, which are fundamental themes discussed in the submitted paper.

Using formation processes to explore low-density sites and settlement patterns: a case-study from the Swabian Jura

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Abstract

Palaeolithic archaeologists often rely on cave and rockshelter sites with rich occupation levels to explore hominin behavior and settlement patterns. However, a closer look into regional occupation data may reveal an uneven distribution of sites and the presence of occupational hiatuses or low-density occupation horizons that often remain understudied. In contrast to this trend, this paper focuses on low-density occupation data to explore regional settlement patterns, using the rich and well-studied Palaeolithic record of the Swabian Jura, Germany, as a case study. In this regard, we employ a geoarchaeological approach based on micromorphology to investigate the formation processes of two low-density occupation sites, Schafstall II and Fetzershaldenhöhle, and compare their formation history with the geogenic sequence from Lindenhöhle. We demonstrate that the investigated sites have comparable formation processes, despite their differences in chronology and context. We argue that humans used Schafstall II and Fetzershaldenhöhle for short-term activities, while the sites mostly served as carnivore activity areas, emphasizing the importance of fauna in the accumulation of thick sedimentary sequences. In addition, our findings corroborate the regional climatic record and provide novel insights into the geomorphological history of the less studied Lauchert Valley, where Schafstall II is located. By comparing our results with data from intensively occupied caves in the Swabian Jura, we provide broader implications for the settlement patterns of Upper Palaeolithic hunter-gatherers. We

conclude with a methodological framework for investigating sites in hunter-gatherer contexts combining a distributional and a site-specific approach.

1. Introduction

The Swabian Jura in southern Germany constitutes one of the landmarks of Palaeolithic archaeology in Europe due to the vast number of cave and rockshelter sites with complex material culture and long occupational sequences spanning the Middle Paleolithic, the Aurignacian, the Gravettian and the Magdalenian (Conard & Bolus, 2003, 2008; Higham et al., 2012; Conard, 2015; Bolus, 2015; Conard, Bolus, et al., 2015; Bolus & Conard, 2019). Hominin habitation in the region is documented along many rivers that dissect the plateau, including the Ach, the Lone and the Lauchert (Fig. 1). However, the distribution of Palaeolithic sites in the Swabian Jura is not uniform but is characterized by qualitative and quantitative differences, both within and between the river valleys. Evidence for occupation appears to be concentrated in the Ach and Lone valleys, located in the eastern part of the Swabian Jura, with a high density of cave sites occupied throughout the Late Pleistocene (Conard et al., 2015). Key sites in the Ach Valley, such as Hohle Fels and Geißenklösterle (Conard & Bolus, 2003, 2006, 2008; Higham et al., 2012; Bataille & Conard, 2018; Taller & Conard, 2019), and in the Lone Valley, such as Vogelherd and Hohlenstein-Stadel (Conard et al., 2003; Niven, 2006; Peyrégne et al., 2019; Kind, 2019; Richard et al., 2020), have been thoroughly investigated and used as a basis to establish the regional chronological and cultural stratigraphy. The link between occupational intensity and settlement patterns has been investigated in detail in this eastern part of the Swabian Jura, with the general trend demonstrating more intense human occupation of the cave sites during the Upper Palaeolithic (Conard, 2011).

Far less is known for the settlement patterns of the Palaeolithic groups in the Lauchert Valley, which is situated in the southwestern part of the Swabian Jura (Fig. 1). Specifically, Palaeolithic archaeology in the Lauchert Valley is characterized by a few sites with intermittent occupation, almost entirely excavated before the 1950s. Moreover, an important number of archaeological finds and excavation documents went missing during the Second World War. These reasons hindered the interpretive potential of the Lauchert sites for exploring the Palaeolithic of the Swabian Jura. To change this picture, researchers from the University of Tübingen re-investigated the archaeological record of the Lauchert Valley by contributing new data through the re-excavation of Schafstall rockshelter (Schumacher, 2014; Conard et al., 2016, 2017; Conard & Toniato, 2018; Toniato, 2021) and by summarizing the available data from the sites of Annakapellenhöhle, Göpfelsteinhöhle and Nikolaushöhle (Toniato, 2021). In this context, Schafstall II constitutes a reference point for the southwestern part of the Swabian Jura, as it is the only Palaeolithic site in the vicinity with a detailed chronostratigraphic and faunal record (Conard et al., 2016, 2017; Conard & Toniato, 2018; Toniato, 2021). According to Toniato (2021), the Lauchert Valley records diachronic differences between the Middle and Upper Palaeolithic in site choice and landscape use. However, the effect of taphonomy on the formation of archaeological deposits in the Lauchert Valley is poorly understood. This also holds true for the different excavation areas of Schafstall II, where it is unclear to what extent the differences in the archaeological record between the new and old excavations are influenced by site use or post-depositional alterations (Toniato, 2021). A major goal of this paper is to investigate the formation processes of Schafstall II rockshelter and provide a geoarchaeological basis for exploring hominin occupation, site integrity and landscape change in the understudied Lauchert Valley.

Even though this is the first time geoarchaeology is applied to a Paleolithic site in the southwestern part of the Swabian Jura, geoarchaeological research has thus far provided essential insights into the formation history and occupational intensity in the eastern part of this region. Site-specific analyses at the key sites of Hohle Fels and Geißenklösterle in the Ach Valley demonstrated that the transition from the Middle Palaeolithic to the Aurignacian reveals a similar record despite the differences in formation processes (Miller, 2015). Erosion influenced the preservation of archaeological deposits in the transition from the late Aurignacian to the Gravettian (Goldberg et al., 2003; Miller, 2015; Goldberg et al., 2019), while erosive processes removing Gravettian material were also recorded in Hohlenstein-Stadel in the Lone Valley (Barbieri & Miller, 2019; Hornauer-Jahnke, 2019). A different approach combining site- and landscape-scale analyses was followed by Barbieri et al. (2018, 2021), who demonstrated that cave erosion is triggered by regional landscape changes for both the Ach and Lone valleys. In this regard, Barbieri et al. (2018, 2021) documented increased cave erosion in the Lone Valley during the Gravettian, calling into question the notion of a decreased human presence in the Lone, in comparison to the Ach, based on lower find densities (Conard et al., 2012). According to these findings, we hypothesize that geogenic processes might have a greater impact on the distribution of Palaeolithic occupation evidence in the valleys of the Swabian Jura than previously assumed. To explore this hypothesis further, a second goal of this paper is to expand the established geoarchaeological framework in the Lone Valley, by investigating the effect of formation processes in two lesser-known sites; Fetzershaldenhöhle and Lindenhöhle. Fetzershaldenhöhle is a carnivore den with minimum anthropogenic input, while Lindenhöhle has an entirely geogenic sequence without human artifacts. The mixed archaeological assemblages and radiocarbon dates in Fetzershaldenhöhle (see Barbieri et al., 2021) and the exclusively geogenic sequence in Lindenhöhle provide an important dataset for identifying the processes that rework and form cave sites in the Swabian Jura.

Overall, this paper draws examples from the well-studied Palaeolithic record of the Swabian Jura to explore the interplay between formation processes and settlement patterns from the perspective of sites with limited to zero human presence.

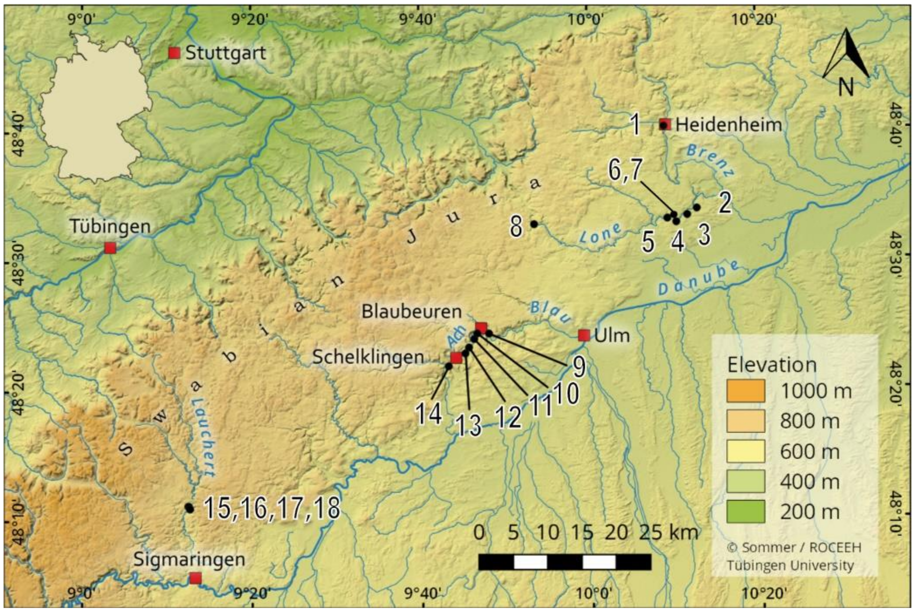

Fig. 1 Map of the Swabian Jura showing the location of the Palaeolithic sites of the Lauchert, Ach and Lone valleys. 1) Heidenschmiede. 2) Langmahdhalde. 3) Vogelherd. 4) Hohlenstein-Stadel. 5) Bockstein. 6) Fetzershaldenhöhle. 7) Lindenhöhle. 8) Haldenstein. 9) Große Grotte. 10) Brillenhöhle. 11) Geißenklösterle. 12) Sirgenstein. 13) Hohle Fels. 14) Kogelstein. 15) Göpfelsteinhöhle. 16) Annakapellenhöhle. 17) Nikolaushöhle. 18) Schafstallhöhle. https://doi.org/10.5281/zenodo.3460301

1.1. Addressing settlement patterns and defining low-density occupation in hunter-gatherer contexts

The analysis of archaeological settlement patterns seeks to explore human behavioral change based on the distribution of the material traces of past human presence across space (Kowalewski, 2008; Feinman, 2015). In this context, artifacts and other archaeological features (such as hearths, storage pits, structures, etc.) constitute the physical manifestations of cultural behavior that, when clustered, form archaeological sites (e.g., Spaulding, 1960; Binford, 1964). In the case of hunter-gatherer societies, ethnographic data provide valuable insights regarding the behavioral choices that form sites and shape cultural landscapes. Hunter-gatherer mobility and subsistence strategies produce a complex mosaic of sites, but in most hunter-gatherer contexts two broad categories of functionally distinct sites emerge; the residential camps and the task-specific sites, such as hunting camps or other logistical locations (Binford, 1979, 1980). Residential camps have a long-term or seasonal occupation, with huts, hearths and other infrastructural features serving as focal points for various social activities (Binford, 1978; O'Connell, 1987; O'Connell et al., 1991; Bartram et al., 1991 among others). Task-specific locations, on the other hand, have a more short-term or ephemeral use, occupied only for the necessary amount of time to perform the task at hand. The archaeological "signature" of residential and task-specific sites differs according to the activities performed and the amount of time spent in a single site, i.e., the occupation intensity. Occupation intensity, which is determined by the length and the frequency of occupation, or the size of the hunter-gatherer group, controls greatly the amount of refuse accumulated in a single site (Munro, 2004). Therefore, the intensive occupation of residential camps results in a high refuse density, while the less intense occupation of task-specific sites results in a low-density record, with discard concentrated over the landscape rather than in recognizable “sites” (Binford, 1979).

The impact of occupation intensity in settlement patterns has been explored widely in the archaeological literature as well, by applying the concept of artifact density as an index of population size and occupation span at a site and landscape level (Treganza & Cook, 1948; O’Connor & Veth, 1993; Varien & Mills, 1997 for a review; Balme, 2014; Clark, 2017; Belardi et al., 2021; Haaland et al., 2021). In this regard, find density values have been used to characterize Palaeolithic sites as high density or low-density occupation contexts, with the distribution of artifacts and features providing implications for site structure and population dynamics. However, the usefulness of density values may be compromised by various formation processes, such as the rate of geogenic deposition (Jerardino, 1995), spatial heterogeneity of activities (Domínguez-Rodrigo & Cobo-Sánchez, 2017), technological changes (Hiscock, 1981), sampling strategy (Binford, 1964) or other methodological factors (Sánchez-Romero et al., 2021). Geoarchaeological approaches investigating the diachronic changes of anthropogenic deposits provide a complementary approach to distributional studies, by focusing on the processes that influence the formation of archaeological contexts as distinct depositional units. The formation processes of caves and rockshelters have received much geoarchaeological attention in this regard, as they often contain rich stratified sequences with good organic preservation (Karkanas et al., 2007; Goldberg et al., 2009; Berna et al., 2012; Miller, 2015).

Overall, high find density caves, rockshelters and open-air sites often monopolize the archaeological narrative of settlement patterns, while low-density sites are largely understudied. In terms of terminology, we define low-density occupations as they are usually described in the literature (Straus & González Morales, 2021): as archaeological sites or levels within sites characterized by a low amount of artifacts per unit of time and by the absence or limited presence of archaeological features. In this paper, we investigate the formation processes of such sites, addressing their potential as interpretative tools for regional settlement patterns.

2. Materials and methods

2.1. The sites

The majority of Palaeolithic cave and rockshelter sites in the Swabian Jura document recurrent hominin occupation with abundant allochthonous materials introduced to the sites by humans. However, for this study, we focused on the site scale analysis of Palaeolithic sites with a limited to zero anthropogenic input. The available sites in the Swabian Jura that fill this criterion are Schafstall II in the Lauchert Valley, as well as Fetzershaldenhöhle and Lindenhöhle in the Lone Valley. Here we provide a brief overview of the research history and the available field data for the respective sites.

2.1.1. Schafstall II

Schafstall rockshelter is located in the Lauchert Valley, close to the town of Veringenstadt (Fig. 1 and Online Resource Figure 1A). It is separated into two areas, Schafstall I and Schafstall II, that were excavated by Eduard Peters during the first half of the 20th century and by Conard, Toniato and colleagues in the course of two campaigns in 2016 and 2017 (Conard et al., 2016, 2017; Conard & Toniato, 2018; Toniato, 2021). The 2016-2017 excavations focused mainly on Schafstall II due to the preservation of intact deposits (Conard et al., 2017) and exposed a stratigraphic sequence of around four meters divided into six geological units (Toniato, 2021). Compacted clays with few bone fragments characterize the base of the stratigraphy (GH 6). The sequence becomes coarser upwards with the transition to a yellowish-brown clayey silt (GH 5), a more clast supported greenish-brown clayey silt (GH 4) and a reddish-brown silty layer with fine limestone clasts (GH 3). GH 2c and GH 2b are two spatially restricted features, of which GH 2b is rich in bone finds. The overlying unit GH 2a is the thickest layer in Schafstall II, as well as the richest in terms of finds, with the majority of them being cave bear bones and few lithic artifacts. GH 2a is probably associated also with cave wall collapse, based on the inclusion of boulder-sized limestone blocks, while to the north the site is flanked by an unstratified deposit of unsorted limestone rubble named '*Hangfazies*' (GH Hf). Higher in the stratigraphy, GH 2a gradually transitions to GH 2, a clayey silt layer rich in cave bear and other Pleistocene faunal remains. GH 1 is the topmost humic layer containing Holocene deposits and small amounts of reworked Pleistocene material. The radiocarbon dates published by Toniato (2021) demonstrate that the lower part of the sequence (GH 4) dates to the Middle Palaeolithic (~43,000 cal BP to ~41,000 cal BP), while the upper part of the sequence spans the Gravettian with GH 2a dating between ~35,000 cal BP to ~31,000 cal BP and GH Hf dating between ~33,000 cal BP to ~32,000 cal BP. The absence of post-last glacial maximum (LGM) deposits and relevant C14 dates implies a hiatus or erosional phase between the deposition of layers GH 1 and GH 2. Despite the presence of a few hominin remains with potential Palaeolithic age (Conard et al., 2016), distinct cultural horizons were not recorded. Schafstall II most probably functioned as a cave bear hibernation den with limited human occupation, evinced only by sporadic lithic artifacts. Furthermore, Toniato (2021) suggests that the assemblage differences between the old and new excavation of Schafstall II could reflect a spatial heterogeneity in the geological processes that shaped the site over time. The new excavations at

Schafstall II investigated an area close to the cliff escarpment, which might be more susceptible to erosion and slope wash than the more protected area of the site excavated by Peters, which is located in the inner part of the rockshelter.

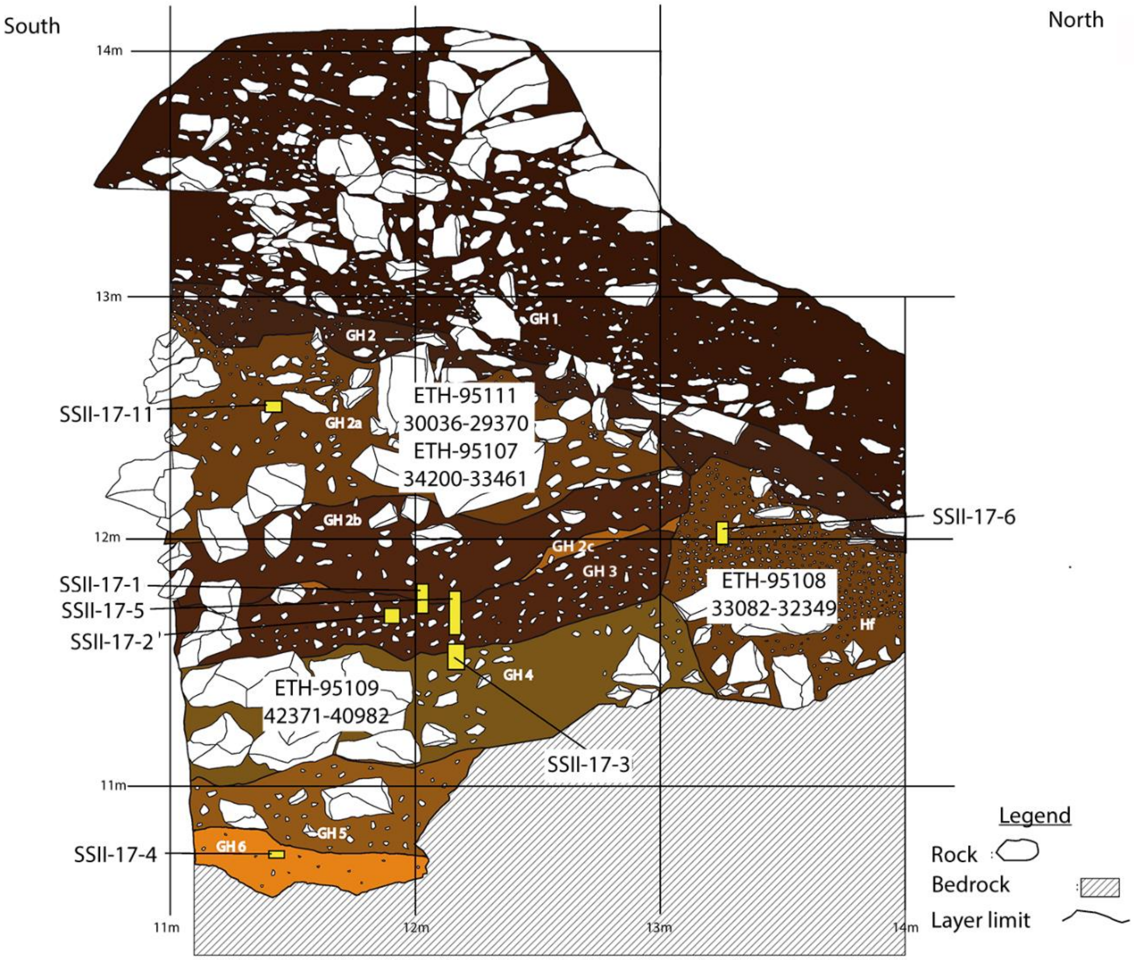

Fig. 2 Stratigraphic sketch of the western profile from Schafstall II modified from Toniato (2021). Includes the radiocarbon dates (in cal BP) published by Toniato (2021), recalibrated according to IntCal20 curve (Reimer et al., 2020), and micromorphology samples. For a field view of the excavation profile and for the location of the micromorphology samples used in this study see Online Resource Figure 2A and 2B

2.1.2. Fetzershaldenhöhle

Fetzershaldenhöhle is located in the Lone Valley (Fig. 1 and Online Resource Figure 1B) and was excavated by Conard and colleagues in 2013 and 2014 (Conard et al., 2015; Conard & Zeidi, 2014). Three lithostratigraphic units comprise a sequence of 1.8 m (Fig. 3), with a clayey silty to silty lowermost unit (GH 3), a clayey silty unit with variable proportions of limestone debris (GH 2) and a topmost heavily bioturbated humic layer (GH 1). GH 1 contains mixed Holocene and Pleistocene material while more secured deposits come from GH 3 where well preserved Ice Age faunal remains and Palaeolithic artifacts were found (Conard et al., 2015). The zooarchaeological study of Lykoudi (2018) suggests limited anthropogenic input in Fetzershaldenhöhle, as the cave was mostly used by carnivores, with cave hyena and wolf being the most probable agents of bone accumulation. Furthermore, Fetzershaldenhöhle is generally associated with a mixed Middle and Upper Palaeolithic assemblage (Barbieri et al., 2021 Supplementary Appendix A; Benjamin Schuerch, personal communication 2022), which is also evident by the mixed C14 dates (Fig. 3). In this context, it is important to note that all C14 samples come from anthropogenically modified bones, which provide another proxy of human activity in the cave.

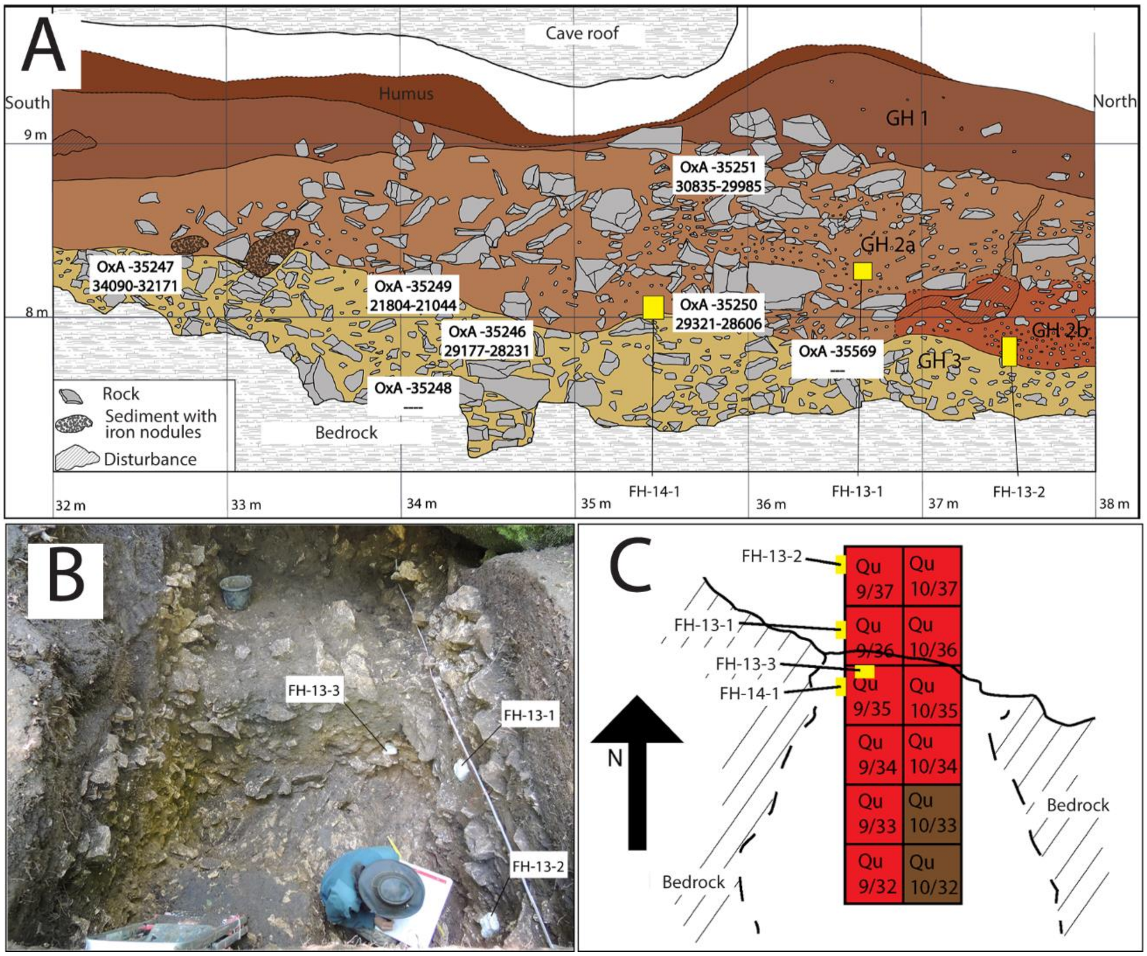

Fig. 3 Fetzershaldenhöhle cave. A) Western stratigraphic profile indicating the approximate location of radiocarbon dates (in cal BP) published by Barbieri et al. (2021) and micromorphology samples. C14 samples OxA-35248 and OxA-35569 are above the upper limit of C14 dating. B) View of the excavation pit looking south with location of micromorphology samples. C) Top-down sketch of excavation quadrants with location of micromorphology samples and outline of the cave brow

2.1.3. Lindenhöhle

Lindenhöhle is a small cave near Fetzershaldenhöhle (Fig. 1 and Online Resource Figure 1C) excavated for one season by a team from the University of Tübingen (Conard & Zeidi, 2014). The about two meters thick sequence (Fig. 4) is separated into 4 lithostratigraphic units (GH 1-4). Clay-rich sediments (GH 4) characterize the base of the sequence, overlain by more than a meter of clast-rich sediments (GH 2-3) and a thinner humic topmost layer (GH 1). No Palaeolithic artifacts were recorded, demonstrating the absence of anthropogenic processes in the cave's depositional formation history (Conard & Zeidi, 2014). Faunal activity in the cave was also rare since only 5 animal bones were collected.

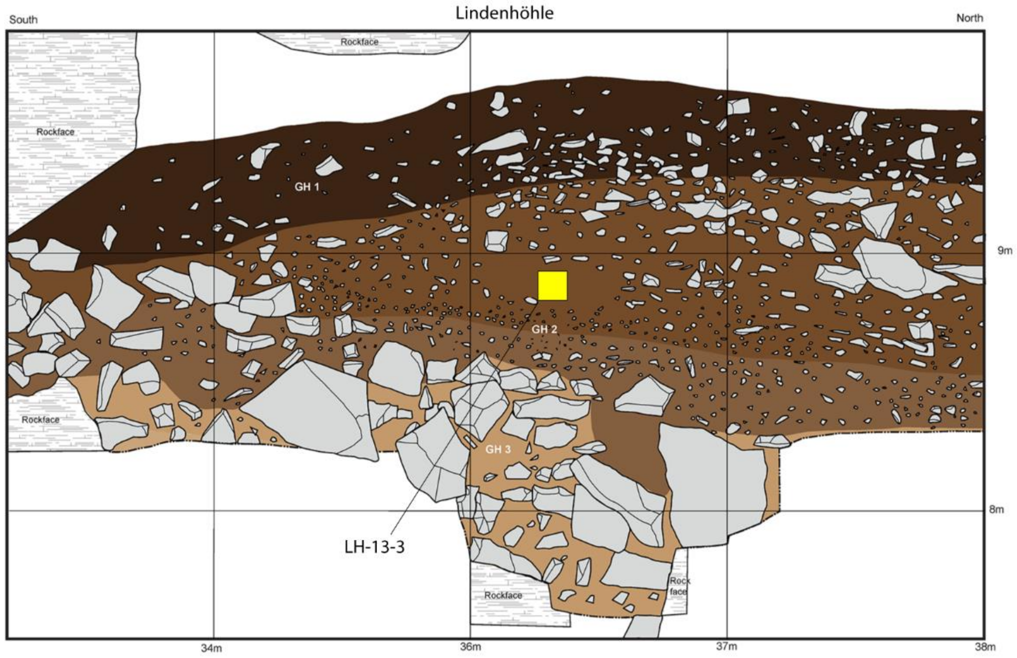

Fig. 4 Stratigraphic sketch of the western profile from Lindenhöhle cave. See Online Resource Figure 2C for a field view of the excavation pit, including the locations of all micromorphology samples used in this study

2.2. Micromorphology

The micromorphology samples were encased in plaster and after extraction were wrapped with paper and packaging tape to ensure integrity during transport. Initially, the samples were dried in the oven at 40°C and impregnated with a mixture of polyester resin, styrene and methylethylketone peroxide (MEKP) hardener under vacuum. After a period of around 20 days, the block samples reached the required hardness and were sliced into slabs with a rock saw after second heating. Thin sections were produced by Terrascope Thin Section Slides (Troyes, France). The thin section production procedure ended with the mounting of the slabs onto 6x9 cm glass slides and their grinding to about 30µm thickness. For some samples, a third mounting or hand polishing was necessary to obtain the right thickness. The thin sections were initially scanned with a high-resolution flatbed scanner to be documented and examined macroscopically (Haaland et al., 2019). Afterwards, they were studied under a stereoscope (0.65 – 5x magnification), as well as, a petrographic microscope (20-500x magnification) using plane-polarized light (PPL), cross-polarized light (XPL) and oblique incident light. Micromorphological descriptions follow the nomenclature and criteria proposed by Stoops (2003) and Courty et al. (1989). During analysis, the micromorphological thin sections were divided into microstratigraphic units (MUs) that were named after the initials of each cave (Table 1). Detailed micromorphological descriptions for different MU's can be found in Online Resource Table 1.

Site	Lithostratigraphic Unit (LU)	Micromorphology sample	Microstratigraphic Unit (MU)
Schafstall II	GH 1	-	-
	GH 2	SSII-16-1	SS6
	GH 2a	SSII-17-7	SS5
	GH 2b	SSII-17-1 SSII-17-5	SS4
	GH 2c	SSII-17-1 SSII-17-2 SSII-17-5	SS4
	GH 3	SSII-17-5	SS4
	Hf	SSII-17-6	SS4
	GH 4	SSII-17-9	SS3
	GH 5	SSII-17-10	SS3
		SSII-17-4 (Upper)	SS2
	GH 6	SSII-17-4 (Lower) SSII-17-12	SS1
Fetzershaldenhöhle	GH 1	FH-13-1	FH4
	GH 2	FH-14-1	FH3
	GH 3		
		FH-13-2	FH2
		FH-13-3	FH1
Lindenhöhle	GH 1	-	-
	GH 2	LH-13-3	LH4
	GH 3	LH-13-2 (upper)	LH3
		LH-13-2 (lower)	LH2
	GH 4	LH-3-1	LH1

Table 1 Summary table for correlating cave sites, geological horizons (GH), micromorphology samples and microstratigraphic units (MUs)

3. Results

3.1. Schafstall II

MU SS1 corresponds to the lowermost parts of the sequence (GH 6) and is observed in sample SSII-17-12 and the largest part of sample SSII-17-4. MU SS1 is a purely geogenic, matrix-supported sediment dominated by laminated silty clay aggregates mixed in places with sand lenses (Fig. 5A and Fig. 6A). These are typical phreatic sediments deposited by aqueous processes of varying intensity while the cave was under the water table (e.g., Bögli, 1980, p. 196). However, their chaotic microstructure, composed of highly fractured and slumped aggregates in a granostriated b-fabric, indicates that they have been heavily reworked since their original deposition (Fig. 5A and Fig. 6A).

The upper part of sample SSII-17-4 correlates with the transition to the more heterogeneous MU SS2, GH 5. An irregular and erosional contact distinguishes MU SS1 from MU SS2 (Fig. 6A) demonstrating a break in sedimentation and exposure of the MU SS1 surface. MU SS1 sediments and individual laminated silty clay aggregates, are mixed with the MU SS2 sediments, which are characterized by a quartz-rich micromass rich in phosphatic aggregates, including carnivore coprolites, and bone fragments (Fig. 5B and 6A). The carnivore coprolites are probably associated with cave bear excrements given the abundance of cave bears in Schafstall II (Toniato, 2021). Many carnivore coprolites could be also associated with cave hyenas based on published diagnostic criteria, such as the pale yellow color in PPL, the undifferentiated b-fabric and the inclusion of quartz silt (Goldberg & Nathan, 1975; Morley, 2017). Still, some phosphatic grains appear homogeneous without clear diagnostic characteristics. These phosphate grains may originate from various sources such as coprolites, phosphatic rinds and crusts, phosphatized sediments or guano (Karkanas & Goldberg, 2010, p. 530; Miller, 2015; Barbieri & Miller, 2019). Based on the dominance of carnivore coprolites and the absence of other phosphate materials we interpret these grains also as coprolite fragments. The coarse components are frequently granostriated suggesting extensive reworking (Fig. 5C and 5D) probably as a result of cryoturbation. Interestingly, a charred bone was also identified in thin section indicating some possible, yet limited, anthropogenic activity in the rockshelter (Fig. 5C and 5D). Overall, the deposition of biogenic materials into the cave and the onset of anthropogenic and carnivore activity marks the transition to sub-aerial conditions in contrast to the aqueous MU SS1 cave environment.

The frequency of coarse clasts increases in the overlying geological horizons GH 4 and 5, which comprise a single MU, MU SS3, based on the samples SSII-17-9 and SSII-17-10. These clast-supported deposits are characterized by frequent limestone fragments and abundant phosphatic material. The micromass is composed of two types of material: a loessy sediment, identified by the higher abundance of silt-sized quartz and mica mixed with iron-rich clay, and a phosphatized alteration of the loessy sediment that is in places decalcified (Fig. 5E and 5F). Phosphatization, which is usually a result of the reaction of the deposits with organic matter (Karkanas & Goldberg, 2010), had a strong influence on the diagenesis of the deposits and also led to the formation of phosphatic rinds around fallen limestone clasts (Online Resource Figure 3B and 3C; see also Miller, 2015). In comparison to MU SS2, the phosphatic material in MU SS3 is not found as individual aggregates, but rather as macroaggregates that comprise a larger part the deposit. Finally, at a later stage, change of conditions promoted calcification leading to localized cementation of deposits (Fig. 5E and 5F).

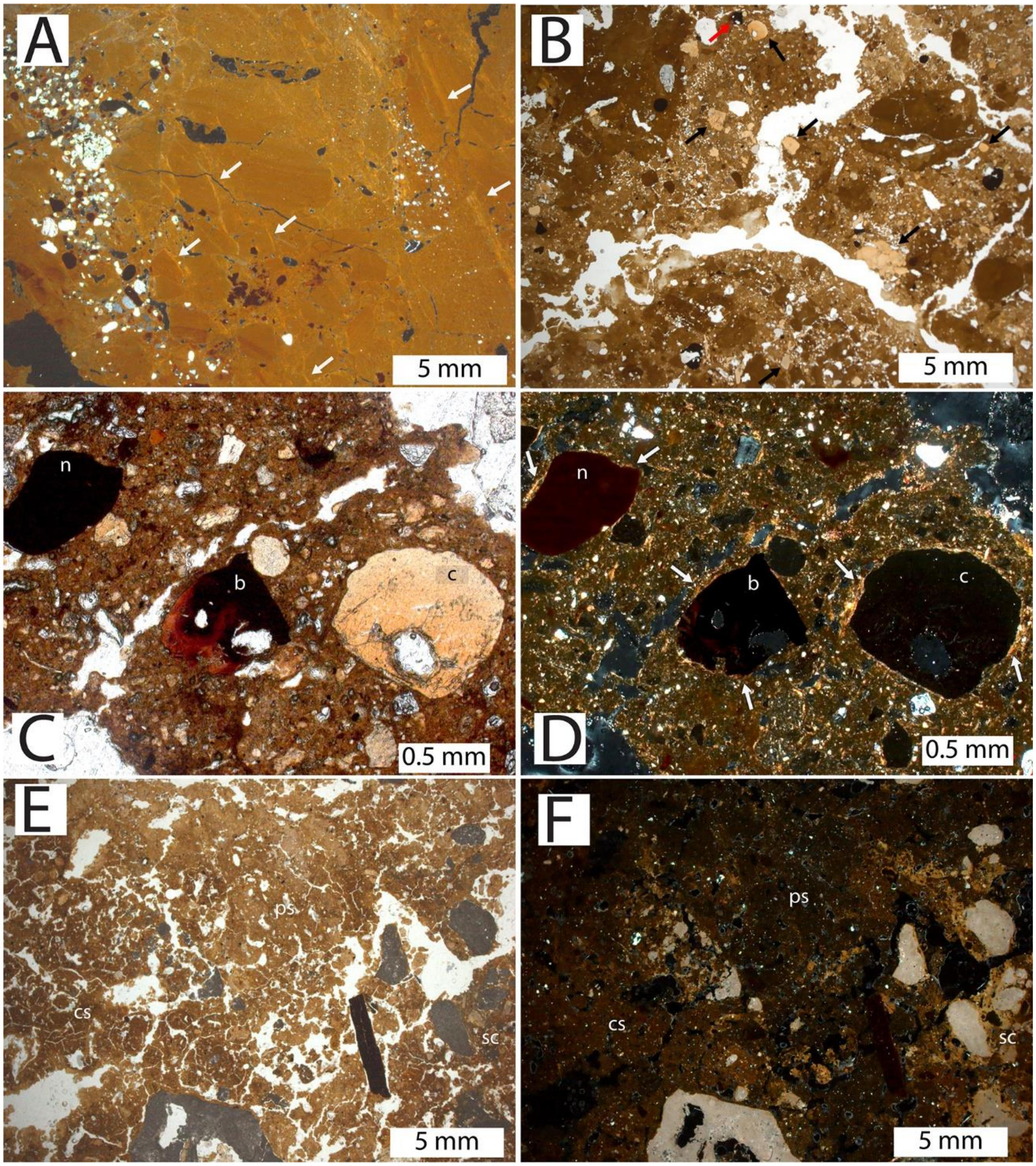

Fig. 5 Schafstall II microphotographs. A) MU SS1; Randomly distributed and fragmented aggregates made of clay and silt together with steeply angled sand lenses form a chaotic microstructure. Arrows indicate oriented clays along shear zones; XPL. B) MU SS2; Note different types of sediment and abundant rounded to subrounded pale brown phosphatic aggregates (black arrows). The red arrow at the top corresponds to the charred bone in C and D; PPL. See also Online Resource Figure 3A for the XPL version of this figure. C) MU SS2; Carnivore coprolite (c), charred bone (b) and iron oxide nodule (n). The optical properties of the charred bone, dark reddish-brown to black in PPL, indicate that it was heated to about 400 degrees (Villagran et al., 2017). D) Same with C but in XPL; notice granostriation around clasts (indicated by white arrows). E) MU SS3; loessy sediment with abundant iron-rich clayey (cs) mixed with a phosphatized and decalcified sediment (ps); PPL. For a lower magnification microphotograph see Fig. S3B. F). Same with E but in XPL; Notice cementation by secondary carbonates (sc). For a lower magnification microphotograph see Online Resource Figure 3C

Despite minor textural variations, GH 3, 2c, 2b and Hf were classified as MU SS4 (samples SSII-17-5, SSII-17-6, SSII-17-1 and SSII-17-2) because they share common characteristics under the microscope. In comparison to MU SS3, MU SS4 has a more calcareous micromass, higher frequency of coarse clasts, but a lower abundance of phosphatic material. According to field observations (Toniato, 2021), GH Hf marks the former dripline and has been accumulated by colluvial processes. Under the microscope, GH Hf has a more open structure with rounded phosphatic grains and bones (Fig. 7A and 7B), but it does not show distinctive micromorphological characteristics that would indicate the action of specific colluvial processes. Overall, MU SS4 is as well characterized by carnivore activity based on the presence of few carnivore coprolites, while the only evidence of anthropogenic activity is a single charred bone in SSII-17-5. Interestingly, dogtooth spar, which is a proxy of de-calcification (Miller, 2015, p. 38), characterizes the rims of some limestone fragments despite the absence of extensive patches of de-calcified sediment as was observed in MU SS3.

The depositional regime in the rockshelter changes with the transition to MU SS5 that corresponds to GH 2a, sample SSII-17-7. MU 5 is the first deposit recorded in the sequence distinguished by a groundmass dominated by well-sorted loess, low frequency of clayey fine material, few pedofeatures and the lack of biogenic inclusions. The homogeneity of this deposit and the good degree of sorting suggests a more ‘primary’ process of loess deposition, most likely reflecting aeolian input. Nevertheless, some reworking is evinced by the inclusion of clay rich aggregates in the coarse fraction, some of which include reworked bones (Fig. 7C and 7D).

The top part of the stratigraphy in GH 2 (MU SS6) is characterized by a matrix supported layer with an iron-rich clay Micromass and loessy coarse component dominated by quartz silt and sand.

In contrast, his deposit is entirely geogenic as it lacks phosphatic aggregates and bones. records a transition.

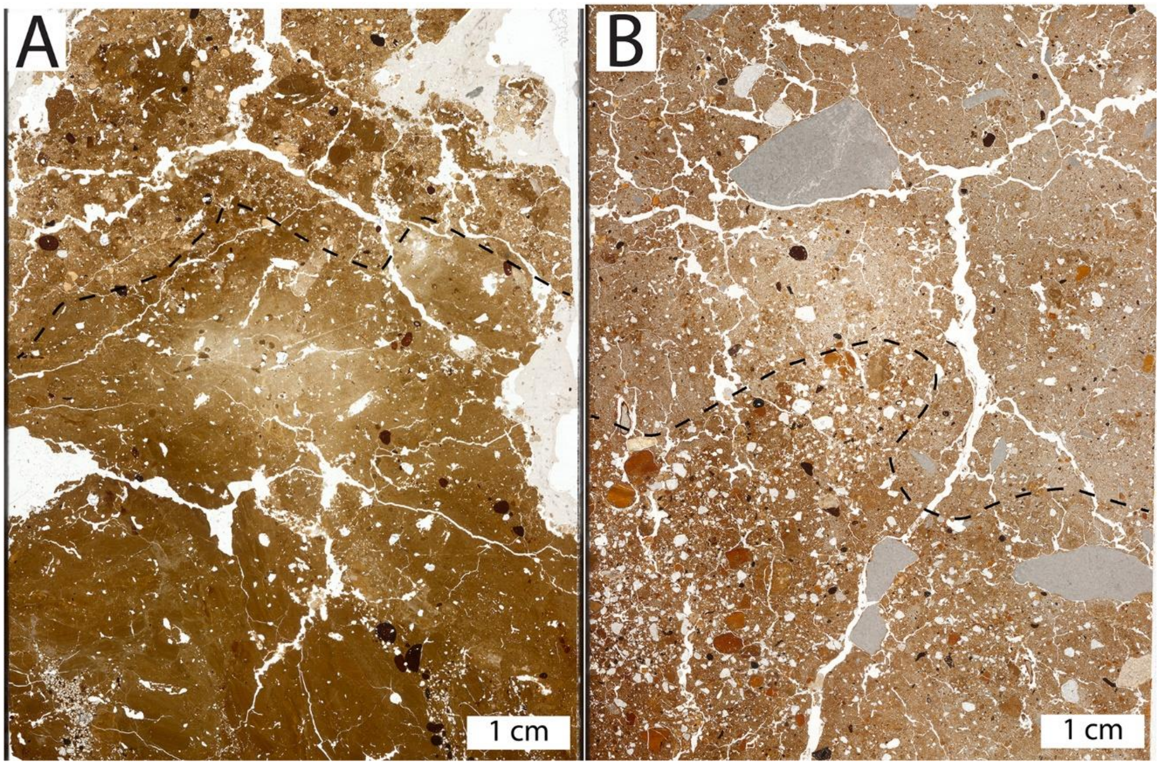

Fig. 6 Flatbed scans from Schafstall II and Lindenhöhle. A) Thin section SSII-17-4 demonstrating the irregular erosional contact (black dashed line) between MU SS1 at the lower half of the thin section and MU SS2 at the upper half respectively. Distorted area at the middle of the sample due to thin section production; PPL. B) Thin section LH-13-2 demonstrating a gradual and irregular erosional boundary (black dashed line) between MU LH 2 at the lower half of the thin section and MU LH3 at the upper half of the thin section; PPL

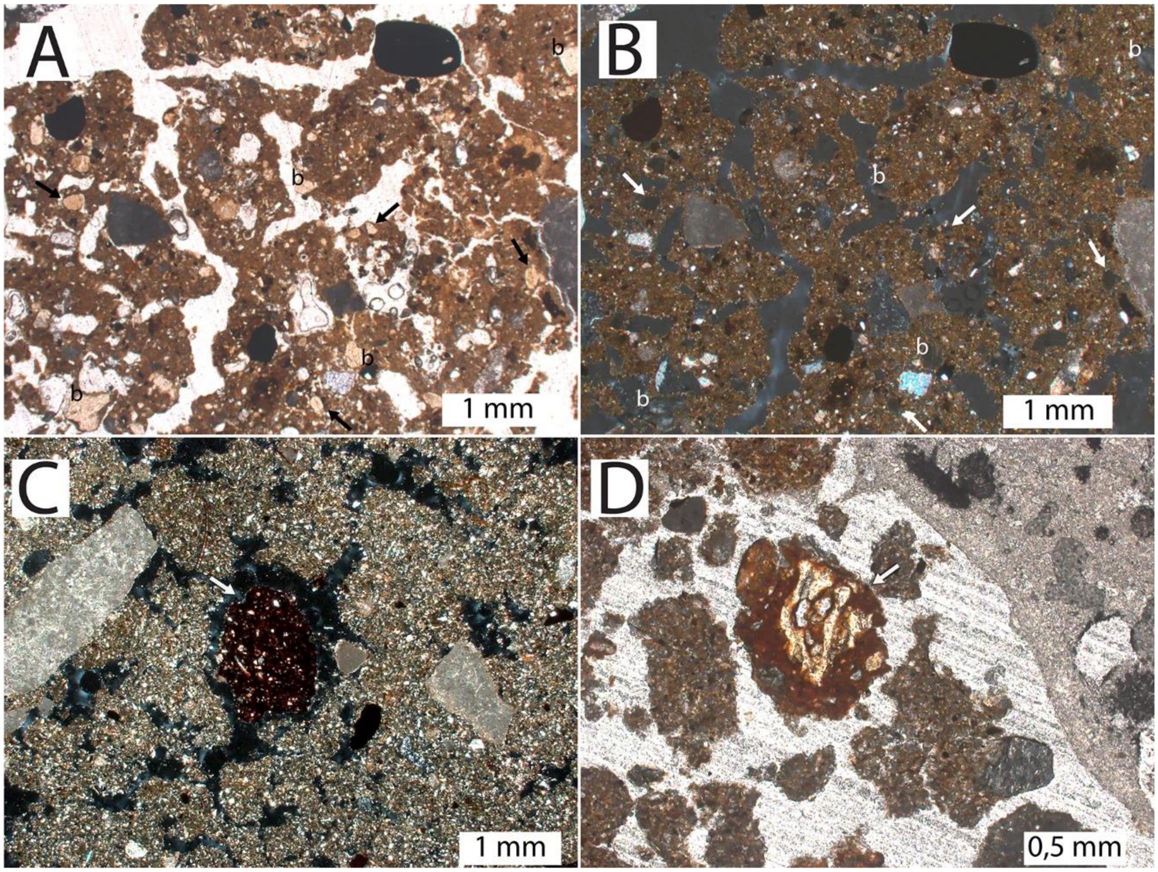

Fig. 7 Schafstall II microphotographs; A) Open fabric of GH Hf with rounded phosphatics (arrows) and bones (b); SSII-17-6, MU SS4; PPL. B) Same with A but in XPL. C) MU SS5; Reworked clay-rich aggregate in a calcitic crystallitic matrix dominated by loess. D) MU SS5; The clay-rich aggregates occasionally include bone fragments

3.2. Fetzershaldenhöhle

MU FH1 corresponds to the lowest part of GH 3, sample FH-13-3. MU FH1 is a clast-supported deposit with a high proportion of sand-sized phosphatic grains, bones and few limestones (Fig. 8 A and 8B). The micromass is stipple speckled, in places striated, with granostriated b-fabric around coarse grains. Carnivore coprolites are common within the phosphatic material, while other phosphatic features include phosphatic coatings around clasts and phosphatic rinds within limestones. The abundance of phosphatic material demonstrates the impact of biogenic processes in the formation of this deposit. The upper part of GH 3, sample FH-13-2, demonstrates a change in sedimentation described as MU FH2. MU FH2 is a distinct clast-supported deposit dominated by angular limestone gravels and few bones in a calcareous loessy micromass (Fig. 8C). The gravels exhibit a horizontal to sub-horizontal orientation and show alterations between coarser and finer units. Their angular shape demonstrates limited movement, but the presence of allochthonous Fe/Mn nodules still demonstrates reworking, probably at a limited scale. MU FH3, sample FH-14-1, covers the transition between GH 3 and GH 2. MU FH3 is characterized by fewer, smaller and more rounded limestone clasts and a more clayey micromass in comparison to MU FH2. The limestone clasts seem to form a series of ellipsoidal alignments, with horizontal to sub-horizontal oriented clasts at the apex of the features and steeply angled clasts at the sides (Fig. 8D and 8E). This arrangement shares similarities with the galaxy structures described by Karkanas (2019) and suggests the preferential rotation of grains in a debris flow. In GH 2, MU FH4 (sample FH-13-1) the amount of coarse clasts decreases significantly. MU FH4 is a matrix-supported layer with an iron-rich brownish-reddish clay micromass and a loess-rich coarse component. It has a homogeneous fabric and is rich in angular bones. Phosphatic features are absent, but the presence of isolated angular phosphatic grains demonstrates the reworking of phosphatic deposits in GH 2 (Fig. 8F).

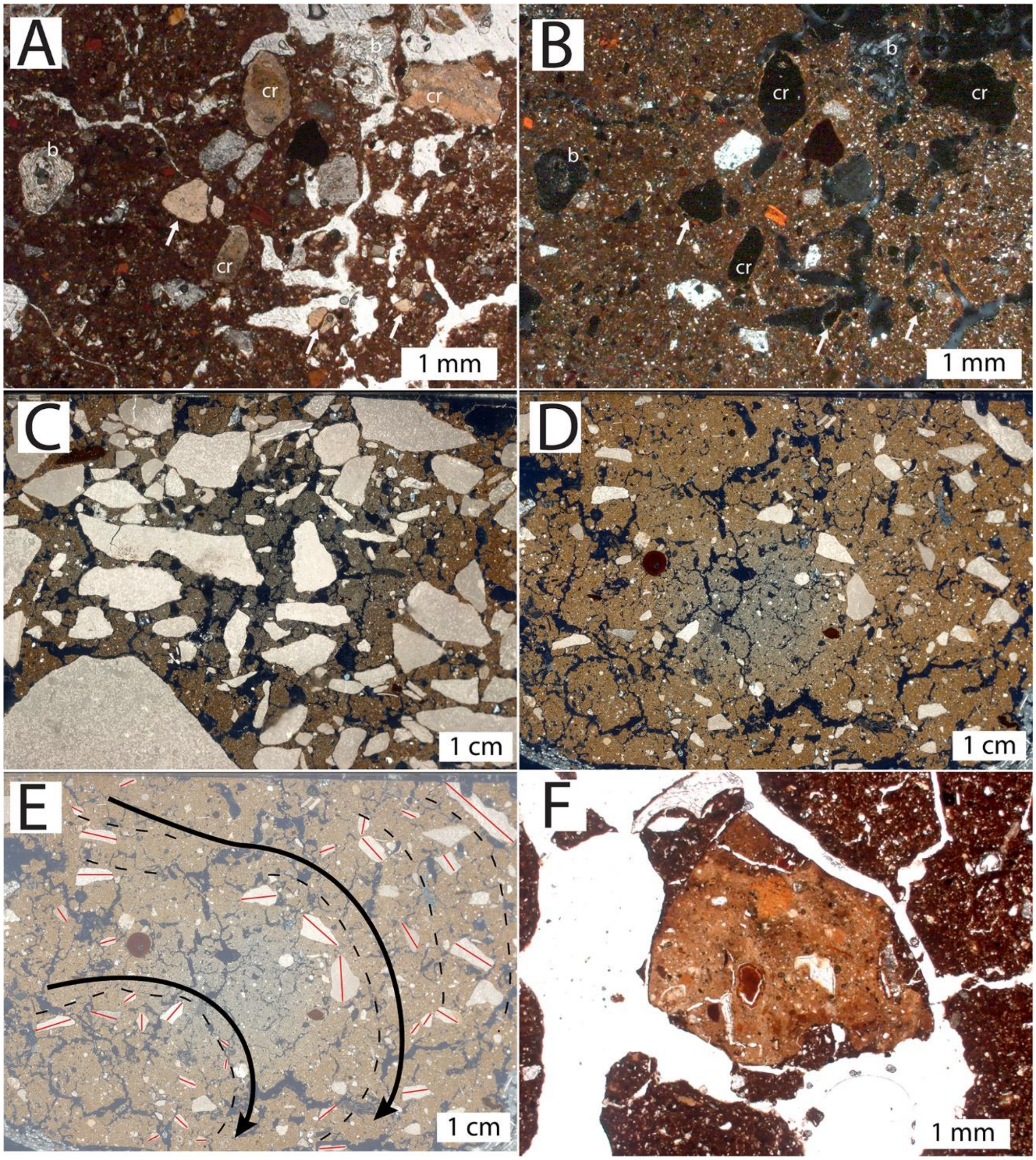

Fig. 8 Photomicrographs from Fetzershaldenhöhle. A) MU FH1; Note the abundance of biogenic components like bones (b) phosphatic grains (arrows) and carnivore coprolites (cr); PPL. B) Same with A but in XPL. C) MU FH2. Abundant limestone gravels, with an angular shape and moderate orientation, show alterations between coarser and finer units and have a relatively uniform dipping; XPL. D) MU FH3; Rotational feature with sketch (E) demonstrating the arrangement of coarse limestone clasts. The clasts might have been rotated around a larger clast outside the extent of the thin section. Red lines show

individual grain alignment, black dashed lines show general grain alignment and solid black lines indicate the direction of flow; XPL. F) MU FH4; Phosphatic grain. The large size and sub-angular morphology demonstrate low degree of reworking prior to deposition; PPL

3.3. Lindenhöhle

MU LH1 corresponds to micromorphology sample LH-13-1, GH 4, the basal unit of the excavated sequence at Lindenhöhle. MU LH1 is a matrix-supported layer dominated by quartz silt and laminated clay fragments in an iron-rich clayey micromass. Areas with well-sorted sand-sized quartz form clast-supported domains that are not layered but reworked in a strongly expressed granostriated or circular striated b-fabric (Fig. 9A). The reworked nature of the MU LH1 and the inclusion of water-lain sand lenses resemble MU SS1 from Schafstall II (Fig. 5A). However, in MU LH1 localized and reworked phosphatized sediment demonstrates the influence of sub-aerial biogenic processes in the formation of this overall geogenic deposit.

Sample LH-13-2 that covers GH 3 consists of two MUs with a gradual and irregular erosional boundary between them, MU LH2 at the lower half of the thin section and MU LH3 at the upper half of the thin section (Fig. 6B). MU LH2 appears to be a coarser variation of MU LH1, since it mainly consists of rounded aggregates of laminated silt and clay, quartz sand and phosphatic sediment (Fig. 9B). On the other hand, MU LH3 is a mixed deposit composed of two types of sediments; a clay-rich reddish sediment covering most of the MU and a more localized, siltier brownish sediment (Fig. 9C). The clay-rich sediments frequently form rounded aggregates that are embedded into the overall sediment structure rather than being loose. The formation of fabric hypocoatings (Fig. 9D), granostriations and, more rarely, downturned silt cappings (Fig. 9E) along the surface of the rounded aggregates demonstrates intense rotational action. These rotational features together with the development of a weak platy microstructure at the bottom of the unit indicate reworking by limited post-depositional freeze-thaw processes, probably solifluction (Goldberg et al., 2003; Miller, 2015; Van Vliet-Lanoë, 2010). The depositional regime in the cave seems to change with the transition to MU LH4 whichcorresponds to GH 2, sample LH-13-3. MU LH4 is a homogeneous geogenic deposit without reworked inclusions or phosphatic sediment. It has a loess-rich micromass with a high clay component expressed in stipple-speckled or striated b-fabrics and dusty clay coatings (Fig. 9F).

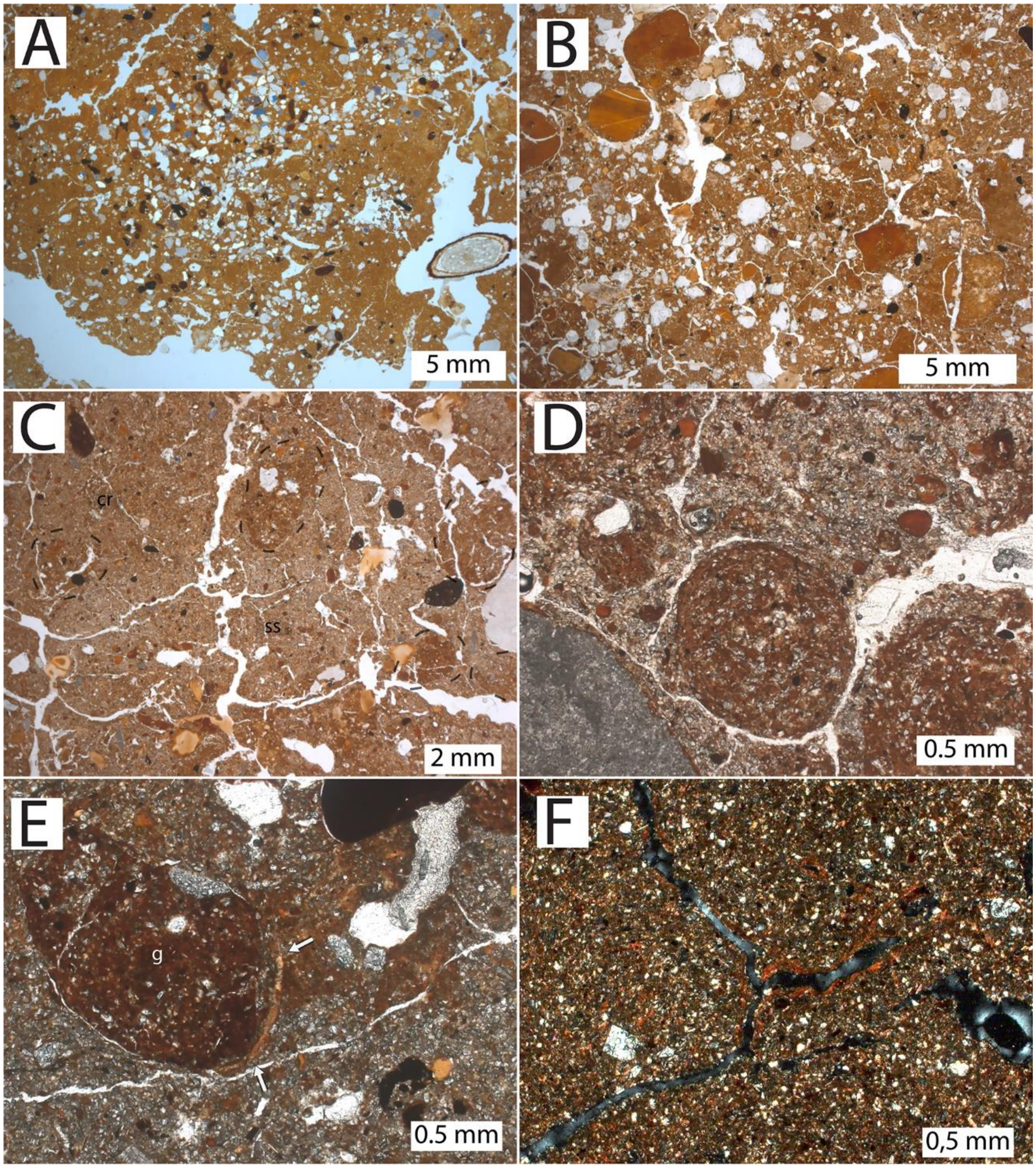

Fig. 9 Microphotographs from Lindenhöhle. A) MU LH1; Iron-rich clays with clast-supported domains made of quartz sand (center of figure); PPL. B) MU LH2; Notice coarser grain size in comparison to MU LH1 (Fig. 3A); PPL. C) MU LH3; Reddish clay-rich sediment (cr) mixed with a lossier sediment (ss). Notice weakly expressed platy voids and some rounded aggregates incorporated into the clay-rich sediment (black dashed lines); PPL. D) Rounded aggregates with fabric hypocoatings; PPL. E) Rounded aggregate (g) with downturned silt capping (arrows); PPL. F) MU LH4; Dusty clay coatings along channels; XPL

4. Summary and discussion

Field excavations and radiocarbon dating demonstrated that the examined caves have a diverse archaeological and chronological context. Schafstall II is a low-density site with a reliably dated stratigraphic sequence, Fetzershaldenhöhle is also a low-density site but with mixed deposits and radiocarbon dates, while Lindenhöhle has no anthropogenic material or radiocarbon dates. Despite this variability, the identification of unique micromorphological fabrics in each site facilitates the investigation of distinct formation processes that elucidate their depositional and post-depositional history. Below, we provide a synthesis of the site formation processes in Schafstall II, Fetzershaldenhöhle and Lindenhöhle (Fig. 9), and we discuss the implications of the observed processes in the context of the regional climatic record. Schafstall II plays a key role in this synthesis as it provides the longest and most secure stratigraphic sequence, with geoarchaeological implications for the relatively understudied Lauchert Valley. Finally, we discuss the implications that low-density sites have for regional settlement patterns.

4.1. Synthesis of site formation processes and palaeoclimatic implications

4.1.1. The low-density sites of Schafstall II and Fetzershaldenhöhle

Among the studied sites, entirely geogenic sediments associated with phreatic conditions and constant water flow are found only in the basal unit of Schafstall II, GH 6. Phreatic deposition in Schafstall II is broadly attributed to the Middle Palaeolithic, although it is impossible to propose a particular age due to the lack of absolute dating from GH 6. In this context, phreatic sediments in the Swabian Jura are not limited to the Lauchert Valley, but have also been found in the Ach Valley. Specifically, they occur in the basal archaeological horizon (AH) VIII in Geißenklösterle (Miller, 2015; Goldberg et al., 2019), dated to around 43-94 ka BP (Richard et al., 2019; Conard et al., 2019) and the Middle Paleolithic layers at Hohle Fels (Miller, 2015), dated to around 70 ka BP (Conard et al. in press).

A key point for the stratigraphic sequence at Schafstall II is the distinct erosional contact marking the transition from phreatic to sub-aerial conditions between GH 6 and GH 5 (sample SSII-17-4). This major transition in the rockshelter environment is best explained by the vertical movement of the Lauchert River during an episode of increased river incision and valley erosion that breached the subterranean karstic chamber and made the rockshelter accessible. Late Pleistocene river incision in the Swabian Jura is generally associated with cold conditions (Barbieri et al., 2018), and, in the case of the Lauchert Valley, Abel et al. (2002) identified several phases of glacially-induced downcutting with the most recent phase spanning the Würm and Riss glaciations until the Holocene. Based on the evidence presented above, we hypothesize that the termination of phreatic deposition observed at Schaftall II is similarly related to a cold event. A radiocarbon date of 42 to 41 Kcal BP from the overlying layer GH 4 provides a *terminus ante quem* for the phreatic/sub-aerial transition in Schafstall II, which is therefore broadly attributed to the Late Middle Palaeolithic. The 48 ky BP Heinrich 5 event (Müller et al., 2011) is the closest cold spell fitting those chronological constraints, but more research on the palaeohydrological evolution of the Lauchert Valley is required to accurately date and interpret the transition recorded at Schafstall II.

The first phreatic/sub-aerial deposits in Schafstall II are found in GH 5 (MU SS2) and are rich in biogenic materials such as carnivore coprolites, phosphatic aggregates and bones. These materials are usually rounded and very often granostriated indicating post-depositional rotation, probably as a result of cryoturbation. The presence of carnivores and hominin combustion activities in MU SS2 is of particular interest as it demonstrates the visit and use of the rockshelter soon after it became accessible. However, anthropogenic contribution in the formation of this layer appears to be limited, since only 1 burned bone was identified in thin section and other anthropogenic materials are absent (e.g., charcoal, lithics). Analysis of the excavated material by Toniato (2021) also points to sparse occupation in GH 5 based on the low number of lithic finds (n=2) and burned bones (<1%).

Deposits rich in biogenic materials such as phosphatic aggregates, carnivore coprolites and bones continue to dominate the upper part of GH 5 and GH 4 (MU SS3). These deposits appears to have accumulated under warm and moist conditions based on the abundance of iron-rich clay and the complicated post-depositional history involving clay pedofeatures, phophatization/decalcification and cementation (Miller, 2015). The wet and moist conditions identified in MU SS3 probably characterized the terminal Middle Palaeolithic in the Lauchert Valley, based on the dates between 42 and 41 Kcal BP from GH 4. However, micromorphological evidence for wet and moist conditions during the end of the Middle Palaeolithic are not exclusive to the Lauchert Valley, but they are also reported in the Ach Valley at the sites of Hohle Fels and Geißenklösterle (Miller, 2015; Goldberg et al., 2019). In this context, the transition from the Middle Palaeolithic to the Aurignacian in the Swabian Jura is generally associated with occupational hiatuses (Sirgenstein; Hohle Fels; Geißenklösterle; Vogelherd; Conard & Bolus, 2006) or very scarce occupation (Hohlenstein-Stadel; Kitagawa, 2014). This trend has been interpreted as a proxy for depopulation, even though the reasons for this depopulation are still poorly understood (Conard & Bolus, 2003, 2006, 2008; Conard, 2011; see also discussion in Bertacchi et al., 2021, p. 10).

In Schafstall II, sedimentary inputs and formation processes seem to vary slightly between GH 4 (MU SS3) and the overlying units GH 3, GH 2c, GH 2b and GH Hf (MU SS4). Even though the frequency of biogenic components is comparable, MU SS4 has a coarser groundmass and a higher loess component that could indicate a transition to cooler conditions. GH Hf has a Gravettian age of about 33 to 32 Kcal BP, while GH 3, GH 2c and 2b were deposited earlier than this date as they are intersected by GH Hf (Fig. 2). An insight into Gravettian sediments in the examined caves is also provided by the lower part of GH 3 in Fetzershaldenhöhle, which was dated with radiocarbon to 34-32 Kcal BP. MU FH 1 has a similar composition to MU SS3 and MU SS4 at Schafstall II, as is it also rich in phosphatic aggregates, carnivore coprolites, and bones. Overall, the deposits that can be securely associated with the Gravettian in both Schafstall II and Fetzershaldenhöhle provide evidence of cold conditions and freeze-thaw processes, given the presence of rounded phosphatic aggregates with granostriated b-fabrics. These findings come in agreement with several lines of evidence that suggest cooling throughout the Upper Palaeolithic (Rhodes et al., 2018; Riehl et al., 2015; Ziegler, 2019) and the Gravettian (Krönneck, 2012; Münzel et al., 2011; Münzel, 2019; Riehl et al., 2015) in the Swabian Jura, corroborated also by micromorphological analysis (Miller, 2015; Goldberg et al., 2019).

A shift in site formation processes occurs with the transition to the late Gravettian in both Schafstall II and Fetzershaldenhöhle. In Schafstall II, the frequent biogenic inclusions that characterized the sequence from GH 5 until GH 2b ceased abruptly with the onset of loess deposition in GH 2a (MU SS5). GH 2a has a chronological range of 34-29 Kcal BP, but field data suggest unclear stratigraphic associations given a probable contiguous deposition with GH Hf (Toniato, 2021). Our micromorphological analysis demonstrated that GH 2a was most probably deposited after GH Hf and closer to the end of the Gravettian, since it is clearly distinct from the biogenically rich MU SS4 sediments that were deposited before 31 Kcal BP based on the date from GH Hf. MU SS5 is a homogeneous well-sorted loess sediment devoid of pedofeatures that reflects a shift to a colder and drier climate towards the end of the Gravettian. This finding corroborates with the study of Barbieri et al. (2018), who monitored a rise in the occurrence of loess in the Swabian Jura, around 29 kcal BP for the Lone Valley and around 32 kcal BP for the Ach Valley. Despite this cold flux, the presence of lithic artifacts in GH 2a demonstrates human activity at the site during this time period (Toniato, 2021).

The homogeneous loess layer identified in Schafstall II is missing from Fetzershaldenhöhle. Sediment reworking is much more pronounced in Fetzershaldenhöhle, based on the presence of mixed radiocarbon dates from GH2, which include a Late Gravettian date of about 30-28 Kcal BP and a much younger date of about 21 Kcal BP (see Fig. 3). Our micromorphological analysis confirms large scale reworking in GH 2 by identifying three distinct depositional fabrics in close proximity; MUs FH2, FH3 and FH4. MU FH 2 is dominated by gravel-sized angular limestone fragments indicating an episode of cave wall collapse, MU FH 3 is a clast supported sediment that provides evidence for mass movement processes and MU FH 4 is a matrix-supported sediment composed almost exclusively of iron-rich clay. It is important to note that despite their textural differences, MUs FH2, FH3 and FH4 have few biogenic components and phosphatic features and thus differ greatly from the early Gravettian deposits of MU FH1. Interestingly, the structural breakdown and remobilization processes documented in MU FH2 and MU FH3 provide evidence for the erosion of the cave and its’ deposits, which coincide temporally with the phase of hillslope erosion in Lone Valley monitored by Barbieri et al. (2018) about 29 Kcal BP.

In the Swabian Jura, cave sediments are usually absent during the LGM, which according to different palaeoclimatic syntheses has an upper limit of 27.2 to 23 Kcal BP and a lower limit of 23.5 to 19 Kcal BP (Sanchez Goñi & Harrison, 2010). Evidence attesting to the LGM are missing from Schafstall II, but are present in Fetzershaldenhöhle based on the radiocarbon date of 21 Kcal BP in GH 2. The association of erosional processes with LGM deposits in Fetzershaldenhöhle confirms the findings of Barbieri et al. (2018, 2021), who argued that the absence of LGM occupation in the Love Valley reflects more the erosion of cave sediments rather than a hiatus of human occupation in the region.

The top part of the stratigraphy described as MU SS6 in Schafstall II and MU FH 4 in Fetzershaldenhöhle shows clear similarities between these two caves. These deposits are characterized by an iron-rich clayey matrix with an increased loess content in the coarse material. This unit is rather homogeneous in Schafstall II, while in the case of Fetzershaldenhöhle it also contains bone inclusions. Even though these sediments are heavily bioturbated, incorporation of reworked material was only observed in Fetzershaldenhöhle indicating lower energy depositional processes most probably associated with a low-grade input of slope material. The abundance of pedogenic clay in the form of clay coatings and infillings suggests more humid conditions.

4.1.2. The geogenic sequence at Lindenhöhle

The geogenic sequence at Lindenhöhle has many similarities with the low-density deposits described in Schafstall II and Fetzershaldenhöhle. First, sub-aerial biogenic components (phosphatic aggregates) mixed with reworked aggregated karstic sediments are also found in the lower parts of the sequence at Lindenhöhle, specifically in GH 4 (MU LH1) and the lower part of GH 3 (MU LH2). The geogenic phreatic aggregates in MU LH1 and MU LH2 are rounded and granostriated suggesting cold conditions. The few phosphatic aggregates that were found in MUs LH1 and LH2 indicate the deposition of some biogenic components in addition to geogenic deposition. However, they have an undiagnostic fabric and therefore cannot be associated with carnivore coprolites or a specific animal activity. Overall, the phreatic/sub-aerial deposits in Lindenhöhle (MUs LH1 and LH2) resemble MU SS2 under the microscope, but lack the limited anthropogenic input recorded in Schafstall II. MU LH 3 in Lindenhöhle records the most extensive cryoturbation features of the investigated deposits, maintaining the general cooling trend observed in MUs LH1 and LH2. MU LH4 in Lindenhöhle has an exclusively geogenic component with an increased clay content similar to MU SS6 in Schafstall II and MU FH 4 in Fetzershaldenhöhle. The lack of radiometric dating hinders the association of the identified processes in Lindenhöhle with a specific chronology. However, based on fabric analogies between Lindenhöhle, Schafstall II and Fetzershaldenhöhle, we could speculate a very approximate age range for the Lindenhöhle sequence extending from the terminal Middle Palaeolithic to the Gravettian.

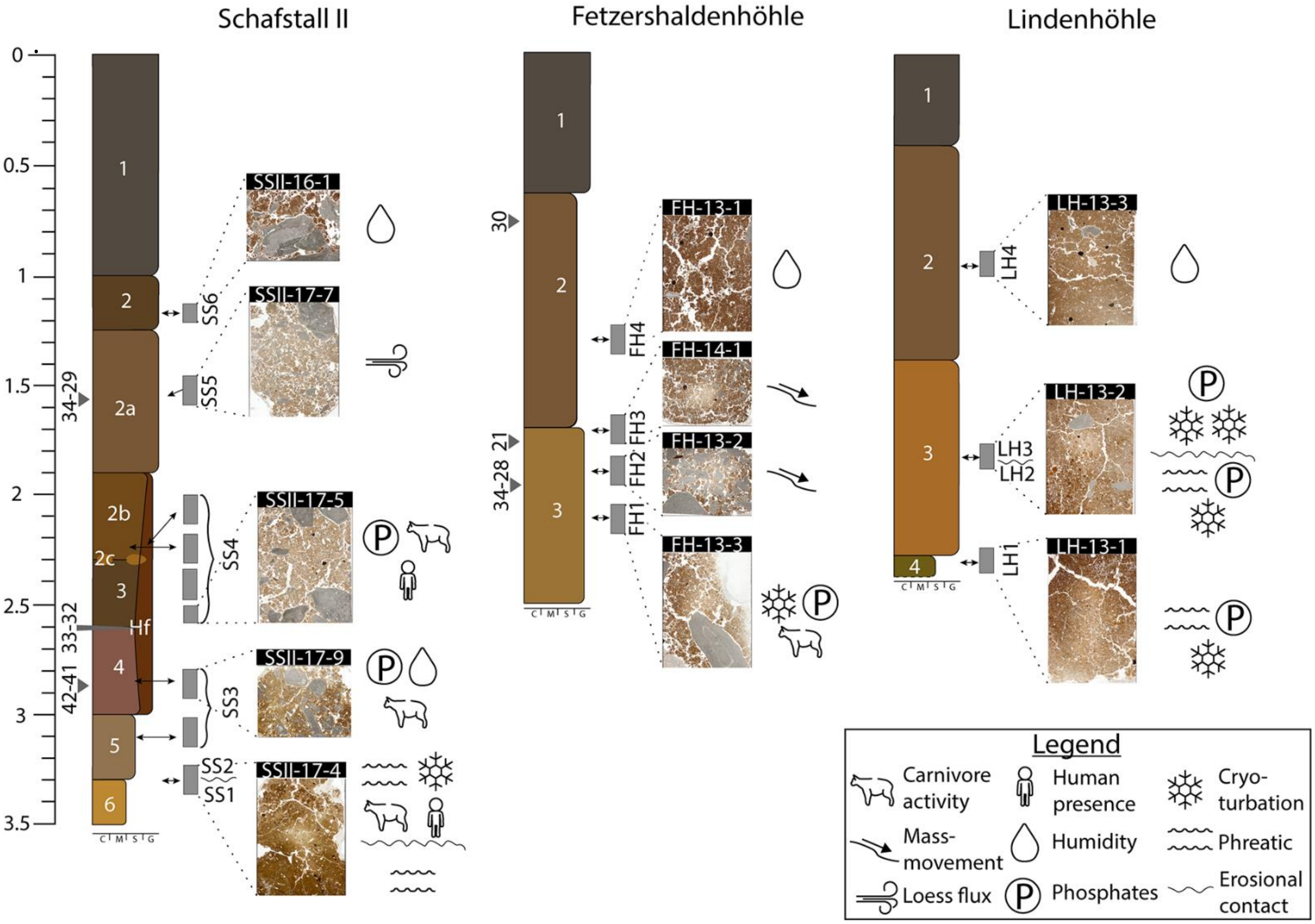

Fig. 10 Summary stratigraphic logs of the excavated sequences from Schafstall II, Fetzershaldenhöhle and Lindenhöhle. To the right of each log location of micromorphology samples followed by MU classification and main microstratigraphic features. To the left of the logs from Schafstall II and Fetzershaldenhöhle C14 dates in Kcal BP

4.2. Low-density sites and Palaeolithic settlement patterns in the Swabian Jura

A view on the settlement patterns of the Swabian Jura demonstrates a complex picture of site occupation in the Middle and Upper Palaeolithic (Conard, 2011). Few sites are occupied continuously throughout the Late Pleistocene, with the work of Barbieri et al. (2018, 2021) demonstrating that geogenic processes eroded cave sediments and influence the integrity of the archaeological record on the landscape scale. However, occupational hiatuses or low-density occupation horizons don't always reflect geological processes, but rather hominin intentionality.

The antagonistic relationship between carnivores and hominins over caves appears to be particularly important for hominin settlement patterns and the formation of dense occupation horizons in the Swabian Jura. Many cave sites have more punctuated human presence (Haldenstein, Conard et al., 2012, p. 239)) as they also functioned as hyena or cave bear dens (e.g., Große Grotte, Münzel & Conard, 2004a; Hohlenstein-Stadel, Kitagawa, 2014, p. 204; Kogelstein, Ziegler in Böttcher et al., 2000; Conard et al., 2015) especially during the Middle Palaeolithic. More intense human occupation in the region during the Upper Palaeolithic (Conard, 2011), led to increased confrontation between humans and carnivores (Camarós et al., 2016; Kitagawa et al., 2012; Münzel & Conard, 2004b, 2004a) and probably contributed to the decline and local extinction of cave bears by the LGM (Münzel et al., 2011; Stiller et al., 2019). A seasonal occupation of caves in the Ach and Lone valleys, as suggested by zooarchaeological data (Münzel & Conard, 2004b; Niven, 2007; Geiling et al., 2015; Münzel, 2019; Bertacchi et al., 2021, p. 12), would imply that carnivores could use the caves when humans were not there. Overall, the increased human presence over the Swabian Palaeolithic is associated with a decrease in the amount of faunal material accumulated in the caves by carnivores (Conard, 2011; Camarós et al., 2016), demonstrating that the role of carnivores as depositional agents is influenced by the settlement patterns of the Palaeolithic groups.

In this context, our micromorphological analysis in Schafstall II, Fetzershaldenhöhle and Lindenhöhle complemented the excavation data and provided new insights into the formation history of these sites. Regarding the Schafstall rockshelter, Toniato (2021) proposed that hominin intentionality or geogenic processes induced variation in the archaeological assemblage between the inner and the outer area of Schafstall II, but did not provide a conclusive interpretation. The cryoturbation that we identified in Schafstall II could have reworked partially specific deposits, but it does not appear to be of sufficient magnitude to change the archaeological sequence dramatically. Therefore, we suggest that the differences in the spatial distribution of the remains identified by Toniato (2021) do not reflect post-depositional reworking by geogenic processes, but differences in site use by both humans and animals. In the case of Fetzershaldenhöhle, we provided additional evidence for carnivore denning corroborating the findings of Lykoudi (2018). Biogenic activity had a depositional effect also in the formation of Lindenhöhle, in addition to the geogenic component reported by Conard & Zeidi (2014). Overall, three basic characteristics define the low-density record of Schafstall II and Fetzershaldenhöhle.

1) The lack of anthropogenic features and anthropogenic sediments even on the microscale, which in the case of the Swabian Jura range from combustion by-products to dumping,

trampling and other site maintenance activities (Schiegl et al., 2003; Goldberg et al., 2003; Miller, 2015).

2) The rare occurrence of certain geogenic processes that have rendered the sites uninhabitable during specific intervals. The first process is associated with the karstic conditions that characterize the basal unit in Schafstall II (GH 6), and the second process is associated with the roof collapse event that was documented in the upper part of GH 3 in Fetzershaldenhöhle.
3) The increased presence of fauna and carnivores.

Below, we discuss the impact of carnivores as depositional agents and the occurrence of low-density sites in Palaeolithic settlement patterns.

4.2.1. Carnivores as depositional agents

Monitoring carnivore activity in thin section is achieved by identifying the deposition of phosphate-rich biogenic materials such as feces, urine and bones (Karkanas & Goldberg, 2010). These materials are incorporated into the sediment as primary phosphates (e.g, coprolites, bones, or guano) or they can form secondary phosphates by dissolving and replacing the original calcareous cave groundmass. However, contrasting geochemical and taphonomic processes influence the formation and preservation of primary and secondary phosphates (Goldberg & Nathan, 1975; Karkanas et al., 2000; Shahack-Gross et al., 2004). Regarding primary phosphates, the fossilization of fecal material necessitates an environment that promotes organic preservation, with the preservation of intact coprolites depending on sediment reworking and bioturbation (Horwitz & Goldberg, 1989). On the other hand, the formation of secondary phosphates requires an acidic environment that facilitates organic matter degradation and water availability that will promote the circulation of the dissolved chemical compounds (Goldberg & Nathan, 1975; Karkanas et al., 2000; Goldberg et al., 2003; Shahack-Gross et al., 2004).

In the Swabian Jura, phosphate grains and phosphatized sediments are observed throughout all the cave sequences examined with micromorphology (Goldberg et al., 2003; Miller, 2015; Goldberg et al., 2019; Barbieri & Miller, 2019), but their distribution varies throughout the Palaeolithic. In more detail, even though secondary phosphates and phosphatized loess are found in both the low-density Middle Palaeolithic and the higher-density Upper Palaeolithic deposits in Hohle Fels and Geißenklösterle (Miller, 2015), as well as Hohlenstein-Stadel (Barbieri & Miller, 2019), primary phosphates in the form of carnivore coprolites are more abundant in the Middle Palaeolithic. Since both primary carnivore coprolites and secondary phosphatized sediments indicate exposure of surfaces to biogenic input, they could be both used as proxies to demonstrate alternating hominin occupation and animal denning (Miller, 2015). However, the formation and preservation of secondary phosphates is more susceptible to local geochemical and climatic changes, with warm and wet periods leading to sediment phosphatization and cold and dry periods to non-phosphatization (Shahack-Gross et al., 2004; Miller, 2015). In contrast, at least in the case of the Swabian sites, the increased presence of carnivore coprolites during the Middle Palaeolithic does not appear to reflect diagenetic changes, but rather serves as a proxy for carnivore activity, corroborating the absence of anthropogenic features and other archaeological evidence that suggest lower population density and less intense use of caves during this period (Miller, 2015). In Schafstall II and Fetzershaldenhöhle, carnivore activity is documented by phosphatic grains associated with coprolite fragments, while phosphatization is identified only in some sediments from Schafstall II. Therefore, based on the available data from the Swabian Jura and the present study, we suggest that primary phosphates may constitute a more robust proxy for identifying carnivore activity, in contrast to secondary phosphates whose formation is dependent upon diagenesis.

Even though primary phosphates are not affected greatly by chemical diagenesis, reworking processes may induce difficulties in the interpretation of carnivore coprolite material with optical microscopy. In our case study, assigning the carnivore coprolites into species-level proved problematic, due to the fragmentation of the coprolite material into homogeneous grains without clear diagnostic characteristics as a result of cryoturbation. In the case of Schafstall II, we assume that the majority of the coprolite material originates from cave bears, since cave bear comprises the most abundant taxon of the faunal assemblage (Toniato, 2021). In the case of Fetzershaldenhöhle, hyenas are probably the dominant agent of coprolite deposition, given that the site served as a hyena den (Lykoudi, 2018). The importance of cave bears and hyenas in the formation of the examined cave sites is not surprising, since both animals are established depositional agents in Paleolithic cave sites. Hyenas typically accumulate large amounts of animal and human bones, as well as organic-rich feces, in their dens (e.g., Horwitz & Smith, 1988; Kerbis-Peterhans & Horwitz, 1992; Stewart et al., 2021). In many Pleistocene caves with a mixed human-hyena occupation, multi-disciplinary studies have demonstrated that hyena activity is one of the main processes of site formation while anthropogenic influence in the site assemblage might be limited (Discamps et al., 2012; Mangano, 2011 and references therein; Maroto et al., 2012; Samper Carro & Martínez-Moreno, 2014; Crezzini et al., 2016; Sanz & Daura, 2018; Villa et al., 2010; Sala et al., 2021). In parallel, many Palaeolithic cave sites are dominated by bear remains as a result of cave bear hibernation or denning, while in some cases the accumulation of bear remains is also attributed to human predation (Münzel & Conard, 2004a; Kitagawa et al., 2012; Romandini et al., 2018; Münzel, 2019). Cave bear denning may lead to extensive phosphatization of sediments (Kurtén, 1976, p. 97; Braillard et al., 2004) and introduce various vegetal residues in cave sites (Rellini et al., 2021).

Despite the absence of anthropogenic features and the minor input of anthropogenic material, Schafstall II, Fetzershaldenhöhle and Lindenhöhle have thick stratigraphic sequences. Phosphate materials deposited by fauna and especially carnivores comprise a major component of the sediments in Schafstall II and Fetzershaldenhöhle, while they are also present in low numbers in

Lindenhöhle, indicating the importance of these biogenic agents in building thick stratigraphic sequences (see also Varis et al., 2022).

4.2.2. A framework for investigating low-density sites in hunter-gatherer contexts

Despite the presence of carnivore-related materials, hominin artifacts are found in both Schafstall II and Fetzershaldenhöhle, although in small numbers. Taking Schafstall II as an example, micromorphology has shown that cryoturbation is common in the Middle Palaeolithic to early Gravettian deposits, which might have resulted in the mixing between the frequent carnivore denning materials and the scarce hominin artifacts. However, the inclusion of hominin artifacts in homogeneous layers with little sediment mixing, such as the loess layer of GH 2a or the clay-rich layer of GH 2, probably demonstrates the superimposition of hominin occupation and bear denning horizons. Analogous interpretations, focusing on the formation of palimpsests by hominin-carnivore activities, have been suggested for the occurrence of Palaeolithic artifacts in carnivore dens outside of the Swabian Jura (Villa & Soressi, 2000; Morley, 2017; Sanchis et al., 2019). In this regard, understanding the interplay between the anthropogenic and natural processes that form low-density sites provides an essential basis for building further hypotheses regarding site use.

In the case of the Swabian Jura, Schafstall II and Fetzershaldenhöhle have low artifact density and strong evidence of carnivore activity in the absence of major reworking processes. Therefore, it is safe to assume that hunter-gatherer groups occupied these sites sparsely, for short-term stays and activities. In contrast to this low-density record, many Swabian caves seem to document multiple uses and a long-term residential occupation based on the presence of high find densities, archaeological features and space managing activities. However, even within the high-density caves, the frequency of find densities and archaeological features changes throughout their occupation history, indicating changes in the settlement strategies of the local hunter-gatherer groups (e.g. Conard et al., 2012). In the Swabian Jura, settlement strategies are associated with a seasonal pattern of cave use that changed diachronically based on demographic, climatic and cultural factors. However, despite their seasonal use, refitting Gravettian artifacts between caves of the Ach Valley (Conard & Moreau, 2004, p. 42) and shared material culture between the Ach and the Lone valleys (Wolf & Conard, 2015) suggest that caves in both valleys were parts of the same settlement system. This settlement system also included open-air sites, even though the open-air record is very fragmentary in comparison to the cave record (Floss et al., 2017).

From an ethnographic perspective, an ephemeral use of caves and rockshelters by hunter-gatherer groups is not surprising. According to Agnolin's review (2021) on cave use in contemporary hunter-gatherer groups, caves in mid and high latitudes rarely have a residential use, with only a couple of semi-sedentary groups occupying them for a prolonged amount of time over the winter season. On the contrary, caves are frequently used for various short-term and non-residential activities including storage and caching, logistical tasks and rituals (Agnolin, 2021). Even though we cannot extrapolate modern ethnographic parallels directly to Paleolithic hunter-gatherer societies, we should expect a diverse use of caves by Palaeolithic hominins. Variability in site and landscape use would result in localities with different occupation intensities and find densities. In this regard, low-density archaeological levels could provide useful insights into settlement patterns as they could demonstrate single occupation events, rather than palimpsests of activities where multiple activities produce a noisy record (Straus & González Morales, 2021). Short stay occupation events related to hunting activities are also recorded in the Swabian Jura in the case of Haldenstein Cave (Conard et al., 2012) and Schafstall II (Toniato,in preparation).

However, a site-specific approach, although valuable for addressing issues of site formation and hominin occupation in individual sites, is not adequate for investigating the complex mosaic of settlement strategies that characterize hunter-gatherer societies. In order to investigate the non-residential and often ‘off-site’ activity of hunter-gatherers, it is necessary to employ a distributional approach that assesses the frequency of hominin occupation on a regional scale. This could be achieved by applying a method that combines site-formation processes and distributional analyses targeting the whole population of sites over a given region, as outlined below. First, it is necessary to assess the frequency of the regional archaeological record by investigating the statistical distribution of sites on the landscape either by rigorous field survey or by using available survey data. A second step, focusing on the excavation of test-pits on the identified sites, provides a site-specific level of investigation aiming to extract preliminary data regarding the characteristics and intensity of hominin occupation. In this regard, test-pits, although spatially limited, facilitate the gathering of high-resolution data regarding the formation, paleoenvironment and chronology of individual sites. Micromorphology is an integral part of this survey methodology, as it can provide fundamental indications of reworking as well as qualitative and semi-quantitative data regarding the extent of anthropogenic and natural deposition. The outlined approach, centered around field survey and micromorphology, is currently being applied by the PALAEOSILKROAD project that investigates the low-density but relatively understudied region of Kazakhstan (Iovita et al., 2020). By combining field survey, test excavations and micromorphology (Varis et al., 2022) explored the completeness of the archaeological record in the Qaratau mountains of Kazakhstan, demonstrating that the low-density distribution of archaeological sites in the region is potentially affected by the formation processes acting on both the site and the landscape level.

The well-documented valleys of the Swabian Jura, such as the Lone Valley, provide a prime case study for the implementation of this multi-scalar approach, since available survey data indicate that many promising sites remain to be excavated (Glatzle, 2012). In this context, assessing the frequency and the formation processes of low-density sites in the Swabian Jura complements the available high-density occupation data, filling in the gaps for a comprehensive assessment of Middle and Upper Palaeolithic hunter-gatherer groups across the Swabian landscape.

5. Conclusions

Palaeolithic caves and rockshelters with high-density occupation levels dominate the archaeological narratives of settlement patterns and hominin behavior. However, regional studies reveal a more dynamic picture, with a variability in the density of occupation data and the presence of various low-density sites (e.g., Isaac, 1981; Roebroeks et al., 1992; Conard et al., 2004, 2012; Heydari-Guran et al., 2015). In this context, ethnoarchaeological data suggest that sites with ephemeral use and low find densities play a key role in seasonal hunter-gatherer mobility strategies, as they are often used to perform various short-term activities. In this article, we have investigated the formation history of low-density caves and rockshelters and explored their role in regional settlement patterns, using the rich record of the Swabian Jura as a case study.

Our micromorphological analysis demonstrated that the low-density sites of Schafstall II and Fetzershaldenhöhle have a comparable formation history. Specifically, they are characterized by the lack of anthropogenic features, the rare occurrence of geogenic processes that could render the sites uninhabitable, like flooding or rockfall events, and the increased presence of animal activity. These findings are of special importance, since they highlight that the low-density archaeological record observed in Schafstall II and Fetzershaldenhöhle do not reflect geogenic processes that could rework or erode the archaeological material, but rather intentionally limited site use by humans. In this regard, we suggest that understanding the interplay between natural and anthropogenic processes in the formation of low-density sites is an important basis for further investigating their role in hunter-gatherer settlement systems.

In the context of the Palaeolithic of the Swabian Jura, low-density sites may provide snapshots of hunter-gatherer logistical activities, which in the case of Schafstall II probably correspond to short-term hunting stations (Toniato, in preparation). Despite the minimum hominin use, we demonstrated that both Schafstall II and Fetzershaldenhöhle were heavily used by carnivore species, which are important agents for the accumulation of biogenic sediments in the studied sites. The accumulation of biogenic material by carnivore species is the dominant depositional characteristic that distinguishes the low-density records of Schafstall II and Fetzershaldenhöhle from the exclusively geogenic sequence at Lindenhöhle.

In this context, we suggest that identifying primary phosphates, particularly carnivore coprolites, is a more robust proxy of carnivore activity than secondary phosphates, whose formation is influenced by diagenesis. The geogenic deposits that dominate low-density sites are also useful paleoenvironmental archives, and in our case study, they either corroborated previous paleoenvironmental work in the Swabian Jura or introduced new research directions. On this subject, our work in Schafstall II provided novel insights into the formation processes of the

Lauchert Valley, one of the less studied valleys of the Swabian Jura, suggesting a phase of river downcutting during the Middle Palaeolithic.

Finally, we propose that a method that combines a site-specific approach, focusing on the micromorphological analysis of formation processes, with a regional approach, focusing on field-survey and test-pit excavations (e.g., Schneidermeier, 2000), might be suitable for assessing variability in site use and occupation intensity in hunter-gatherer archaeological contexts.

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Conflict of interest statement

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Data availability statement

The author confirms that all data generated or analysed during this study are included in this published article.

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Supplementary Information (SI)

Journal of Paleolithic Archaeology

Using formation processes to explore low-density sites and settlement patterns: a case-study from the Swabian Jura

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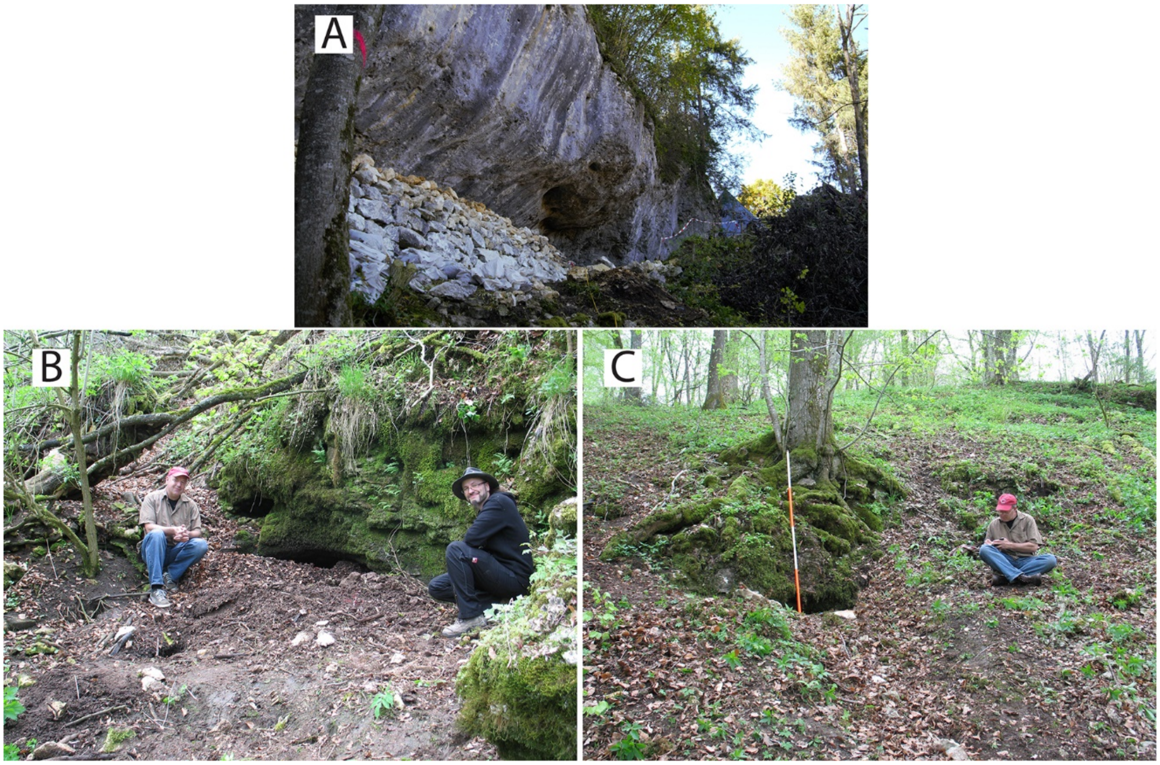
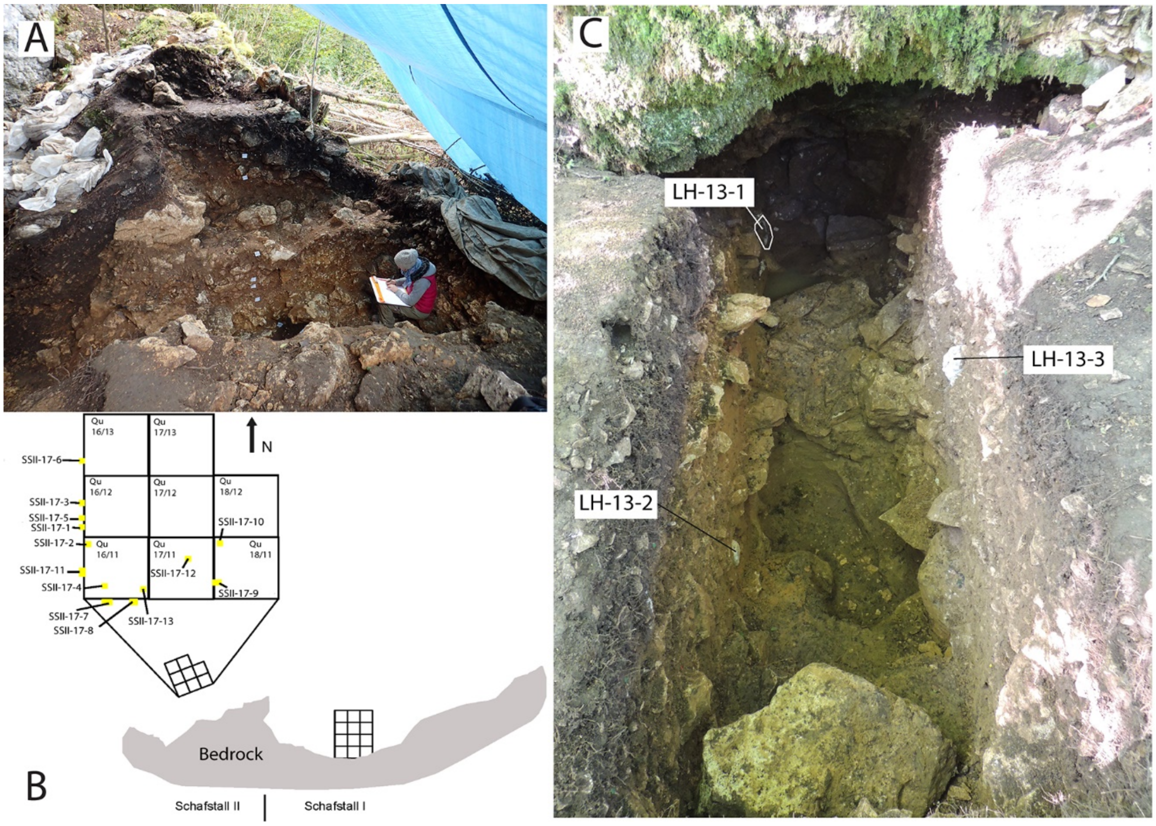
Online Resource Figure 1

Field photos of the sites analyzed in this study. A) Overview of the Schafstall rockshelter where Schafstall I and II are located. B) Fetzershaldenhöhle C) Lindenhöhle.



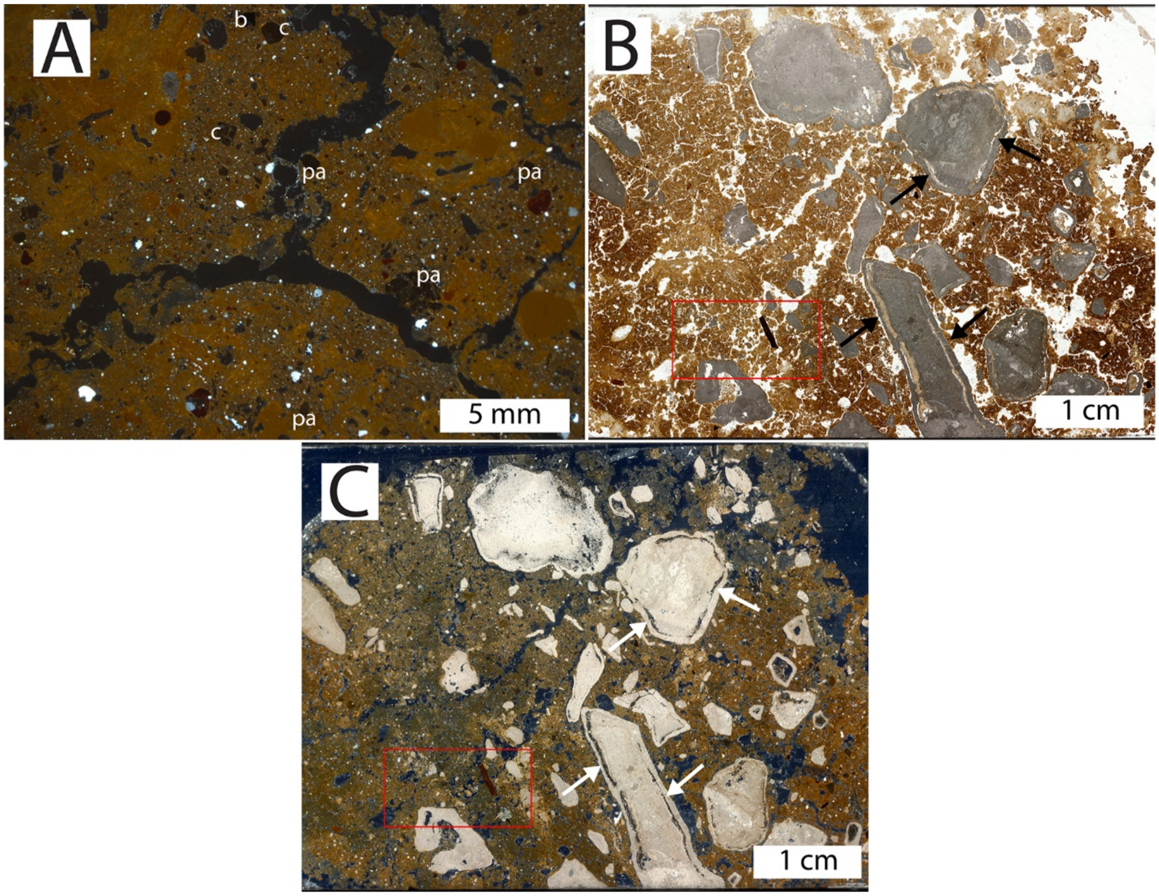
Online Resource Figure 2

Stratigraphic documentation. A) Field view of the western profile from Schafstall II, complementing the stratigraphic sketch of Fig. 2. B) Plan view of the excavation quadrants in Schafstall I and II, demonstrating the location of micromorphology samples used in this study. C) Field view of the excavation pit in Lindenhöhle looking North.



Online Resource Figure 3

Schafstall II thin sections. A) MU SS2; Same as Fig. 5B but in XPL. The phosphatic aggregates (pa) indicated with white arrows in Fig. 5B also include carnivore coprolites (c). B and C) SSII-17-2, MU SS3, in PPL and XPL respectively. Red rectangles correspond to Fig. 5E and 5F. Arrows outline phosphatic rinds developed within the exterior surface of limestone fragments. The phosphatic rinds are pale yellowish in PPL and isotropic in XPL.



Online Resource Table 1

Micromorphology descriptions for the presented thin sections and MUs following the nomenclature proposed by Stoops (2003). Abbreviations:

Texture: S = Silt, VFS = Very Fine Sand, FS = Fine Sand, MS = Medium Sand, Coarse Sand=CS, Very Coarse Sand = VCS, G = Gravel;

Voids: pr = planar, vs = vesicles, vg = vughs, ch = channels, cha = chambers, cp = complex packing voids;

Fabric unit abundance: very few (<5%), *, few (5-15%), **, common (15-30%), ❖, frequent (30-50%),♦ , Dominant (>50%)

			Groundmass			
Site	**Samples**	**Microunit (MU)**	**Coarse material**	**Micromass**	**C/f limit & relative distribution pattern**	**Other descriptive attributes**
Schafstall II	SSII-17-4 (lower)	**SS1**	Quartz (S-G, **)	Iron-rich clay Stipple-speckled	C/f limit: 4µm Monic Close to open porphyric	Voids: vg Pedofeatures: impregnative Fe/Mn oxides; anorthic Fe nodules; Fabric: randomly distributed laminated or graded silty clay sediments, often aggregated, fragmented or slumped; randomly distributed sand lenses; cross-striated & granostriated b-fabrics around silty clay aggregates, Fe/Mn nodules and quartz Microstructure: chaotic
	SSII-17-4 (upper)	**SS2**	Rip-up clasts of SS1 sediments (MS-G, ❖) Phosphatic grains including carnivore coprolites (VFS-VCS, ❖) Quartz (S-VCS, **) Bones (MS-VCS, *) Mica (S, <2%)	Clay Calcitic crystallitic Stipple-speckled	C/f limit: 4µm Close porphyric	Voids: cpv, vg Pedofeatures: impregnative Fe/Mn oxides; anorthic Fe nodules; dusty clay coatings Fabric: common granostriated b-fabric around coarse clasts

					Microstructure: granular, subangular blocky; phosphate clasts have mostly a granular miscrosture but often form macroaggregates
SSII-17-9 SSII-17-10	**SS3**	Limestone fragments (❖) Phosphates including carnivore coprolites (VFS-VCS, ❖) Quartz (VFS-MS, *) Mica (VFS, *) Bones (MS-G, *) Shale fragments (VCS-G, <2%)	Loessy micromass: Mixture of iron-rich clay, calcite & quartz; calcitic-crystallitic Phosphatized & often decalcified loessy micromass, stipple-speckled (>30-40%)	C/f limit: 64µm Open porphyric Fine enaulic	Voids: cp, vg Pedofeatures: anorthic Fe nodules; impregnative micrite; phosphatic rinds around & within limestone gravels Microstructure: granular, subangular blocky; phosphates are mostly macroaggregated
SSII-17-5 SSII-17-6 SSII-17-1 SSII-17-2	**SS4**	Limestone fragments (FS-G, ❖) Quartz (VFS-CS, **) Mica (VFS-FS, *) Bones (MS-VCS, *) Silty clay aggregates (FS-CS, **) Carnivore coprolites (MS-VCS, *) Siliceous rock fragments (MS, <1%)	Loessy micromass: Mixture of iron-rich clay, calcite & quartz, calcitic-crystallitic Phosphatized but not decalcified loessy micromass, stipple-speckled (>20%)	C/f limit: 64µm Open porphyric Fine enaulic	Voids: ch, vg, cp Pedofeatures: dusty clay coatings; anorthic Fe nodules; Fabric: occasionally granostriated b-fabrics around coarse clasts Microstructure: granular, subangular blocky; Other: often limestones demonstrate dog-tooth spar alteration
SSII-17-7	**SS5**	Quartz (VFS-MS,❖) Mica (FS-VFS, **) Limestone fragments (VFS-G, **) Iron-rich sediment/soil aggregates (MS-VCS, *)	Loess: mixture of calcite, quartz & mica with low clay content calcitic-crystallitic	C/f limit: 64µm Fine enaulic	Voids: cp, vg, ch Pedofeatures: dusty clay coatings; anorthic Fe nodules; Fe/Mn anorthic nodules; clay hypocoatings around few coarse clasts. Microstructure: granular

	SSII-16-1	**SS6**	Limestone fragments (MS-G, ◆) Quartz (S-VCS, **) Mica (S-VFS, *)	Iron-rich clay Calcitic-crystallitic	C/f limit: 4µm Open porphyric	Voids: vg, ch Pedofeatures: anorthic Fe nodules; Microstructure: granular, vughy;
Fetzershaldenhöhle	FH-13-3	**FH1**	Phosphatic grains including carnivore coprolites (MS-G, ❖) Limestone fragments (FS-G, **) Quartz (S-VCS, **) Silty clay aggregates (VFS-MS, **) Bones (MS-G, **) Mica (VFS, *)	Iron-rich clay Calcitic-crystallitic	C/f limit: 4µm Open porphyric	Voids: cp, vg, ch Pedofeatures: phosphatic rind within limestone; anorthic Fe nodules; dusty clay coatings & hypocoatings Fabric: common granostriated b-fabrics around coarse clasts and especially silty clay aggregates Microstructure: granular, vughy; phosphates deposited as individual grains
	FH-13-2	**FH2**	Limestone fragments (G, ◆) Quartz (VFS-CS, **) Soil/sediment aggregates (G, **) Mica (VFS-FS, *) Bones (MS-G, *) Phosphatic aggregates including carnivore coprolites (FS-CS, *) Eggshell (CS-VCS, *) Siliceous rock fragments (CS-G, <2%)	Loessy micromass: mixture of iron-rich clay, calcite & quartz, calcitic-crystallitic	C/f limit: 64µm Open porphyric	Voids: ch, vg Pedofeatures: anorthic Fe nodules; dusty clay coatings & hypocoatings Fabric: limestone fragments show horizontal to subhorizontal distribution and moderate orientation; granostriated b-fabrics around coarse clasts Microstructure: subangular blocky
	FH-14-1	**FH3**	Limestone fragments (♦) Quartz (S-CS, **) Bones (MS-G, **) Mica (S-FS, *) Phosphatic aggregates including carninovore coprolites (MS-CS, *) Orange silty clay aggregates (VFS-MS, *) Eggshell (CS-VCS, *)	Iron-rich clay Calcitic-crystallitic	C/f limit: 4µm Open porphyric	Voids: ch, vg Pedofeatures: impregnative Fe/Mn oxides, anorthic Fe nodules; dusty clay coatings & hypocoatings; calcite crusts Fabric: Limestone clasts show ellipsoidal alignments with moderately oriented

			Siliceous rock fragments (CS-G, <2%)			horizontal to subhorizontal clasts at the apex of the features and steeply angled clasts at the sides Microstructure: subangular blocky (weakly developed)
	FH-13-1	**FH4**	Limestone fragments (FS-G, **) Quartz (VFS-MS, **) Mica (S-VFS, *) Bones (MS-G, **, angular) Phosphatic grains (VFS-G, <2%) Orange silty clay aggregates (VFS-FS, <2%)	Iron-rich clay Calcitic-crystallitic	C/f limit: 4µm Open porphyric	Voids: ch, vg, cha Pedofeatures: impregnative Fe/Mn oxides, anorthic Fe nodules; dusty clay coatings & hypocoatings; fabric hypocoatings Microstructure: subangular blocky (weakly developed)
Lindenhöhle	LH-13-1	LH1	Quartz (S-VCS, ❖) Mica (VFS, *) Orange silty clay clasts (VFS-G, **) Phosphatic/phosphatized aggregates (FS-CS, **)	Iron-rich clay, Calcitic-crystallitic Phosphatic and occasionally decalcified, stipple-speckled (10-20%)	C/f limit: 4µm Close to open porphyric	Voids: ch, vg Pedofeatures: granostriated b-fabrics around coarse clasts; impregnative Fe/Mn oxides; anorthic Fe nodules; dusty clay coatings Fabric: phosphatic material occurs as nodules but is mostly macroaggregated; coarse quartz forms clusters Microstructure: channel & vughy
	LH-13-2 (lower)	LH2	Limestone fragments (MS-G, *) Quartz (S-VCS, ❖) Mica (VFS, *) Silty clay clasts (VFS -G, ❖) Siliceous clasts (CS-G, *) Eggshell (MS, *)	Iron-rich clay, Calcitic-crystallitic Phosphatic and occasionally decalcified, stipple-speckled (10%)	C/f limit: 4µm Close to open porphyric	Voids: ch, vg Pedofeatures: impregnative Fe/Mn oxides; anorthic Fe nodules; dusty clay coatings; granostriated b-fabrics around coarse clasts Fabric: chaotic Microstructure: channel & vughy

LH-13-2 (upper)	LH3	Limestone fragments (MS-G, **) Quartz (S-VCS, ❖) Silty clay clasts (VFS -G, **) Mica (VFS, *)	Iron-rich clay, Calcitic-crystallitic Loessy micromass: mixture of clay, calcite & quartz, calcitic-crystallitic	C/f limit: 64μm Open to close porphyric	Voids: ch, vg Pedofeatures: impregnative Fe/Mn oxides; anorthic Fe nodules; fabric hypocoatings Fabric: the iron-rich clay sediments form rounded aggregates; granostriated b-fabrics & downturned silt cappings often form around the rounded clay aggregates Microstructure: subangular blocky (weakly developed)
LH-13-3	LH4	Limestone fragments (G, ♦) Quartz (FS-VCS, **) Mica (VFS-FS, *) Siliceous clasts (CS-G, *)	Loessy micromass: mixture of clay, calcite & quartz, calcitic-crystallitic	C/f limit: 64μm Open porphyric	Voids: ch, vg, pr Pedofeatures: dusty clay coatings & hypocoatings; impregnative Fe/Mn oxides; anorthic Fe nodules Microstructure: subangular blocky (weakly developed)