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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

Paleolithic 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 Paleolithic 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 Paleolithic hunter-gatherers. We conclude with methodological suggestions for investigating sites in hunter-gatherer contexts combining a distributional and a site-specific approach.

Keywords Geoarchaeology · Settlement patterns · Low density · Micromorphology · Palaeolithic archaeology · Human carnivore interactions · Swabian Jura

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Introduction

The Swabian Jura in southern Germany constitutes one of the landmarks of Paleolithic 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 et al., 2015a; 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 Paleolithic 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., 2015a, b). Key sites in the Ach Valley, such as Hohle Fels and Geißenklösterle (Bataille & Conard, 2018; Conard & Bolus, 2003, 2006, 2008; Higham et al., 2012; 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, 2019b; Richard et al., 2020), have been thoroughly investigated and used as a basis to establish the regional chronological

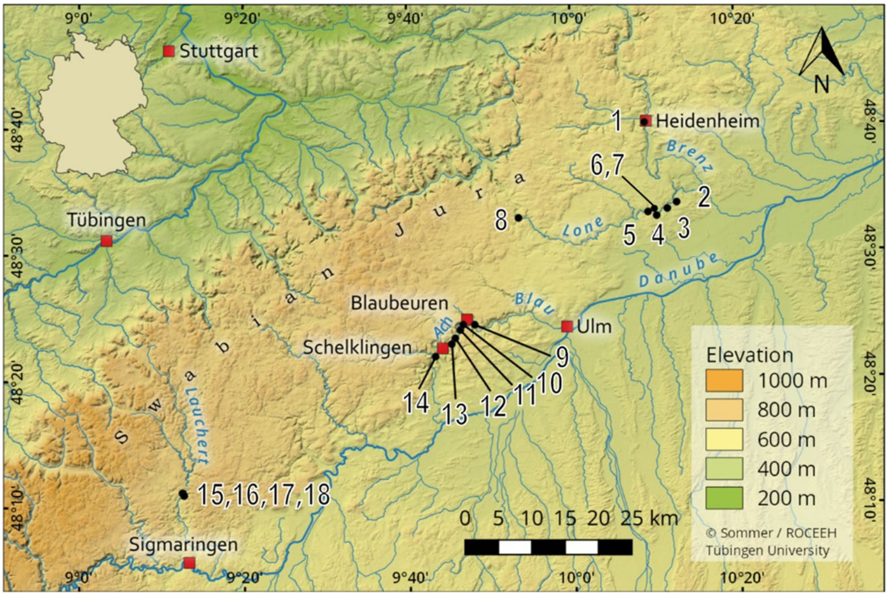

Fig. 1 Map of the Swabian Jura showing the location of the Paleolithic sites of the Lauchert, Ach, and Lone valleys. (1) Heidenschmiede. (2) Langmahdhalde. (3) Vogelherd. (4) Hohlenstein-Stadel. (5) Bockstein. (6) Fetzershaldenhöhle. (7) Lindenhöhle. (8) Haldenstein. (9) Große Grotte. (10) Brillenhöhle.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

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 Paleolithic (Conard, 2011).

Far less is known for the settlement patterns of the Paleolithic groups in the Lauchert Valley, which is situated in the southwestern part of the Swabian Jura (Figs. 1). Specifically, Paleolithic 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 Paleolithic 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 (Conard & Toniato, 2018; Conard et al., 2016, 2017; Schumacher, 2014; 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 Paleolithic site in the vicinity with a detailed chronostratigraphic and faunal record (Conard & Toniato, 2018; Conard et al., 2016, 2017; Toniato, 2021). According to Toniato (2021), the Lauchert Valley records diachronic differences between the Middle and Upper Paleolithic 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 Paleolithic 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, 2019; Miller, 2015), 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 Paleolithic 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 Paleolithic 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.

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 (Feinman, 2015; Kowalewski, 2008). In this context, artifacts and other archaeological features (such as hearths, storage pits, structures) constitute the physical manifestations of cultural behavior that, when clustered, form archaeological sites (e.g., Binford, 1964; Spaulding, 1960).

Various models addressing hunter-gatherer settlement patterns and mobility strategies have been applied in Paleolithic contexts to explain the spatial variability that characterizes archaeological distributions and infer hominin behavior (Binford, 1980; Conkey, 1980; Conard, 2001, 2004; Fitzhugh & Habu, 2002; Meignen et al., 2006; Conard & Delagnes, 2010, 2015) (e.g., Binford, 1980; Conkey, 1980; Fitzhugh & Habu, 2002; Conard, 2001, 2004; Meignen et al., 2006; Conard & Delagnes, 2010, 2015). Among them, Binford's (1979, 1980) and Kelly's (1983) ethnoarchaeological studies distinguishing between logistical and residential mobility have been some of 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 huts, hearths, and other infrastructural features serving as focal points for various social activities (Bartram et al., 1991; Binford, 1978; O'Connell, 1987; O'Connell et al., 1991 among others). Task-specific locations, on the other hand, have a more ephemeral or logistical use, occupied only for the necessary amount of time to perform the task at hand (e.g., hunting, scouting trips, caching). The mobility spectrum suggested by this "forager-collector" model (Binford, 1980) has received many criticisms (Bettinger, 1987; Grove, 2009; Speth, 2022; Whallon, 2006; Wobst, 1978), but still constitutes a useful starting point for disentangling archaeological variability in Paleolithic contexts. Specifically, the archaeological "signature" of residential and task-specific sites might differ according to the occupation intensity, i.e., the length and the frequency of occupation, or the size of the hunter-gatherer group, which control greatly the amount of refuse accumulated in a single site and the composition of archaeological assemblages (Munro, 2004; Yellen, 1977). Therefore, the intensive occupation of residential camps results in a high refuse density over individual sites, while the ephemeral occupation of task-specific sites results in a low-density record, with discard concentrated over the landscape rather than in recognizable "sites" (Binford, 1979; Foley, 1981; Yellen, 1977).

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 Paleolithic 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, such as the application of different statistical tools or methods of recording spatial data (Sánchez-Romero et al., 2021). Geoarchaeological studies 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 (Berna et al., 2012; Goldberg et al., 2009; Karkanas et al., 2007; 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): 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. Although this definition is empirical and qualitative, we believe that a threshold separating low-find density from high-find density sites is context-depended and, therefore, cannot be universally quantified. However, to provide an idea of scale for our case study, in contrast to the approximately 113,800 and 1909 artifacts per square meter (n/m^3) found in the Aurignacian/Gravettian layers in Hohle Fels and Geißenklösterle respectively (Conard et al., 2012), only 430 Upper Paleolithic n/m^3 were found in Schafstall II, while in Fetzershaldenhöhle, only few artifacts are safely attributed to the Pleistocene. In this paper, we investigate the formation processes of such low-find density sites, addressing their potential as interpretative tools for regional settlement patterns.

Materials and Methods

The Sites

The majority of Paleolithic 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 Paleolithic 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.

Schafstall II

Schafstall rockshelter is located in the Lauchert Valley, close to the town of Veringenstadt (Fig. 1 and Online Resource Fig. 1A). It is separated into two areas, Schafstall I and Schafstall II, that were excavated by Eduard Peters during the first half of the twentieth century and by Conard, Toniato, and colleagues in the course of two campaigns in 2016 and 2017 (Conard & Toniato, 2018; Conard et al., 2016, 2017; 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 4 m divided into six geological units (Fig. 2; 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 Paleolithic (~ 42,000 cal BP to ~ 41,000 cal BP), while the upper part of the sequence spans the Gravettian with GH 2a dating between ~ 34,000 cal BP

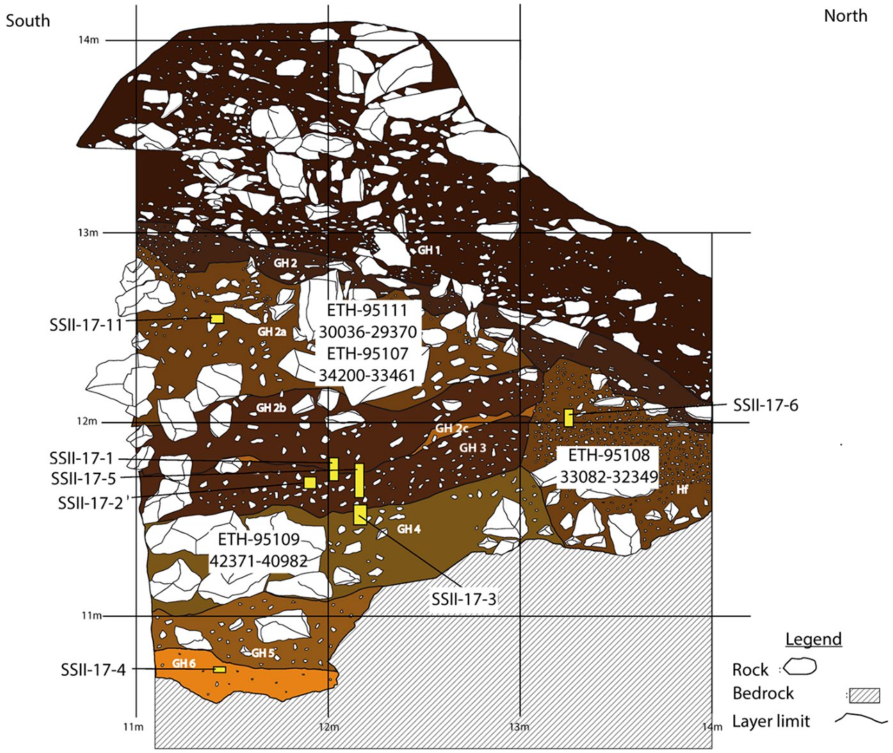

Fig. 2 Stratigraphic sketch of the western profile from Schafstall II modified from Toniato (2021). Includes the radiocarbon dates (in cal BP) published by Toniato (2021), recalibrated according to IntCal20 curve (Reimer et al., 2020), and micromorphology samples. For a field view of the excavation profile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

and ~ 29,000 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 skeletal remains with potential Paleolithic age (Conard et al., 2016), distinct cultural horizons were not recorded because of the low and sporadic distribution of artifacts throughout the sequence. 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.

Fetzershaldenhöhle

Fetzershaldenhöhle is located in the Lone Valley (Fig. 1 and Online Resource Fig. 1B) and was excavated by Conard and colleagues in 2013 and 2014 (Conard & Zeidi, 2014; Conard et al., 2015a, b). 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 Paleolithic artifacts were found (Conard et al., 2015a, b). 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 Paleolithic assemblage (Barbieri et al., 2021 Supplementary Appendix A; Benjamin Schuerch, personal communication 2022), which is also

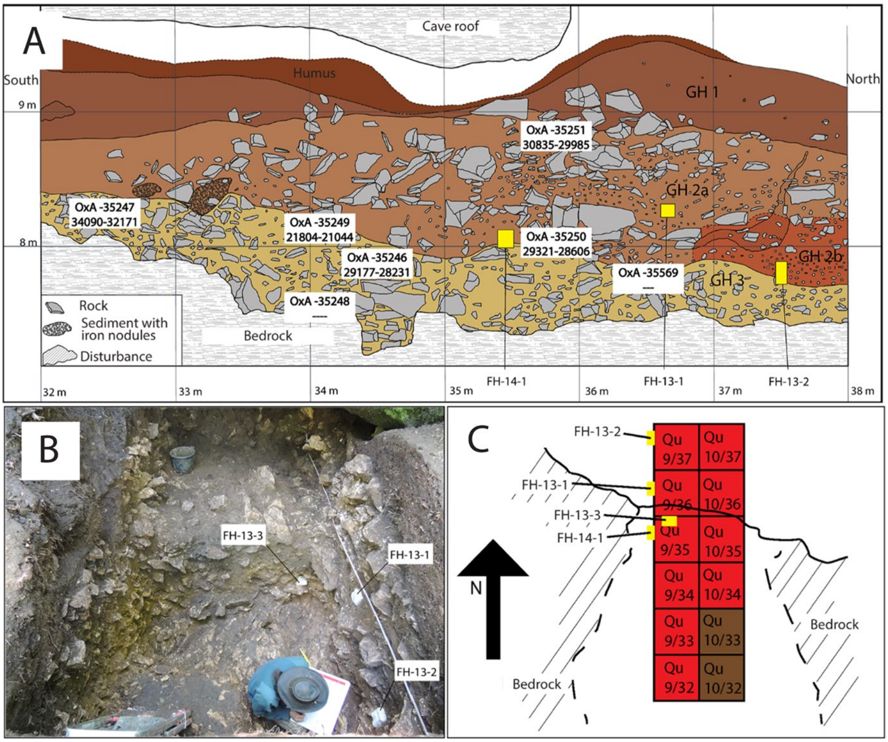

Fig. 3 Fetzershaldenhöhle cave. **A** Western stratigraphic profile indicating the approximate location of radiocarbon dates (in cal BP) published by Barbieri et al. (2021) and micromorphology samples. C14 samples OxA-35248 and OxA-35569 are above the upper limit of C14 dating. **B** View of the excavation 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

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.

Lindenhöhle

Lindenhöhle is a small cave near Fetzershaldenhöhle (Fig. 1 and Online Resource Fig. 1C) excavated for one season by a team from the University of Tübingen (Conard & Zeidi, 2014). The about 2 m 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 Paleolithic 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.

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

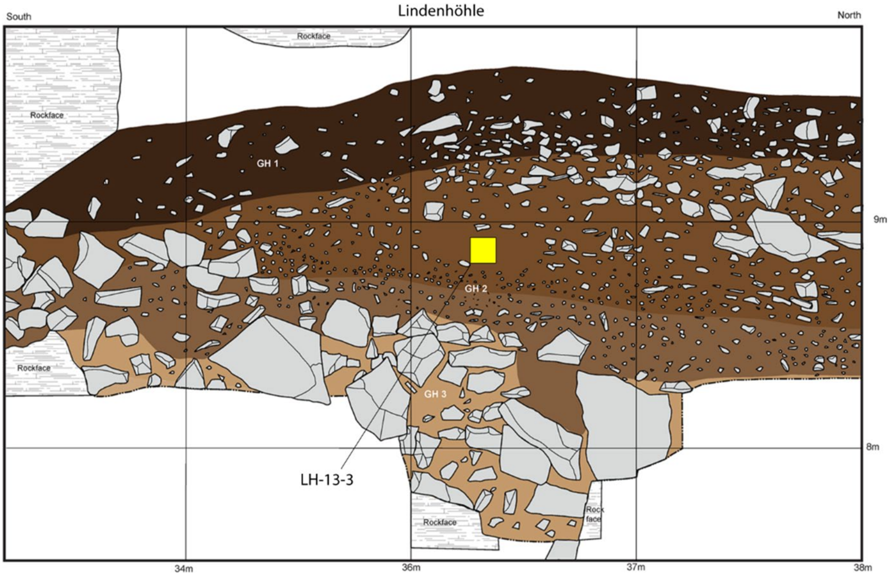

Fig. 4 Stratigraphic sketch of the western profile from Lindenhöhle cave. See Online Resource Fig. 2C for a field view of the excavation pit, including the locations of all micromorphology samples used in this study

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 6 × 9 cm glass slides and their grinding 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 with a high-resolution flatbed scanner to be documented and examined macroscopically (Haaland et al., 2019). Afterwards, they were studied under a stereoscope (0.65–5 × magnification), as well as under a petrographic microscope (20–500 × 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 MUs can be found in Online Resource Table 1.

Results

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 locally mixed with sand lenses (Figs. 5A and 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 (Figs. 5A and 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 (Figs. 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,

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

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

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 mark the transition to sub-aerial conditions in contrast to the more 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,

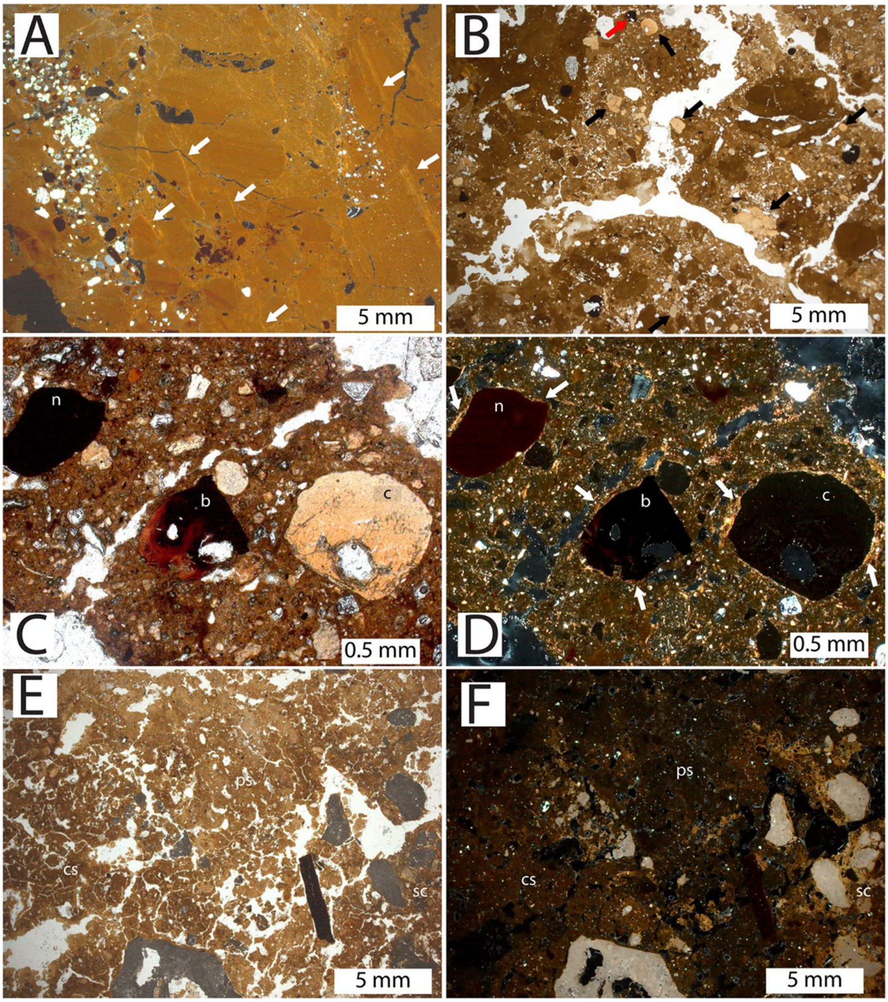

Fig. 5 Schafstall II microphotographs. **A** MU SS1; randomly distributed and fragmented aggregates made of clay and silt together with steeply angled sand lenses form a chaotic microstructure. Arrows indicate oriented clays along shear zones suggesting lateral deformation; XPL. **B** MU SS2; note different 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 Fig. 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° (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 Fig. 3C

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

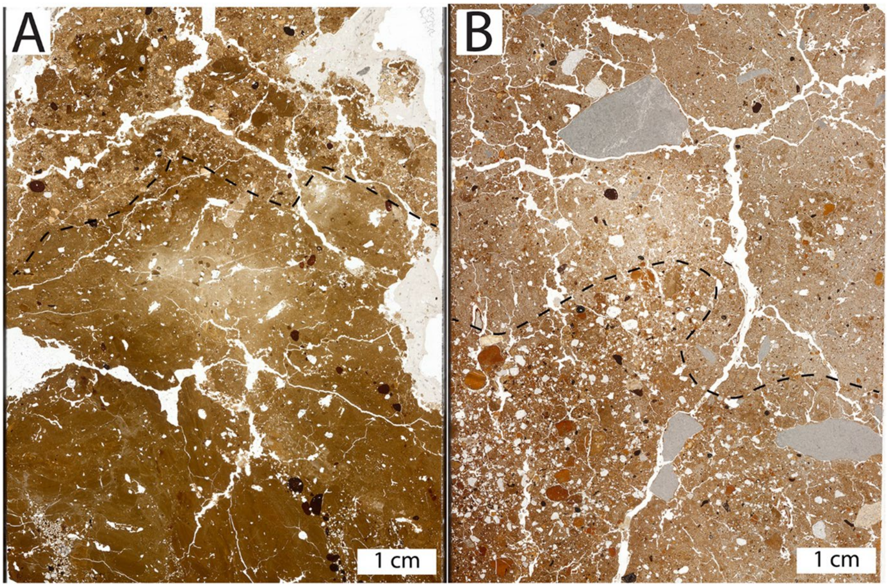

Fig. 6 Flatbed scans from Schafstall II and Lindenhöhle. **A** Thin section SSII-17–4 demonstrating the irregular erosional contact (black dashed line) between MU SS1 at the lower half of the thin section and MU SS2 at the upper half, respectively. Distorted area at the middle of the sample due to thin 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

influence on the diagenesis of the deposits and also led to the formation of phosphatic rinds around fallen limestone clasts (Online Resource Fig. 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 of the deposit. Finally, at a later stage, change of conditions promoted calcification leading to localized cementation of deposits (Fig. 5E and 5F).

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 B), 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 decalcification (Miller, 2015, p. 38), characterizes the rims of some limestone fragments despite the absence of extensive patches of decalcified sediment as observed in MU SS3.

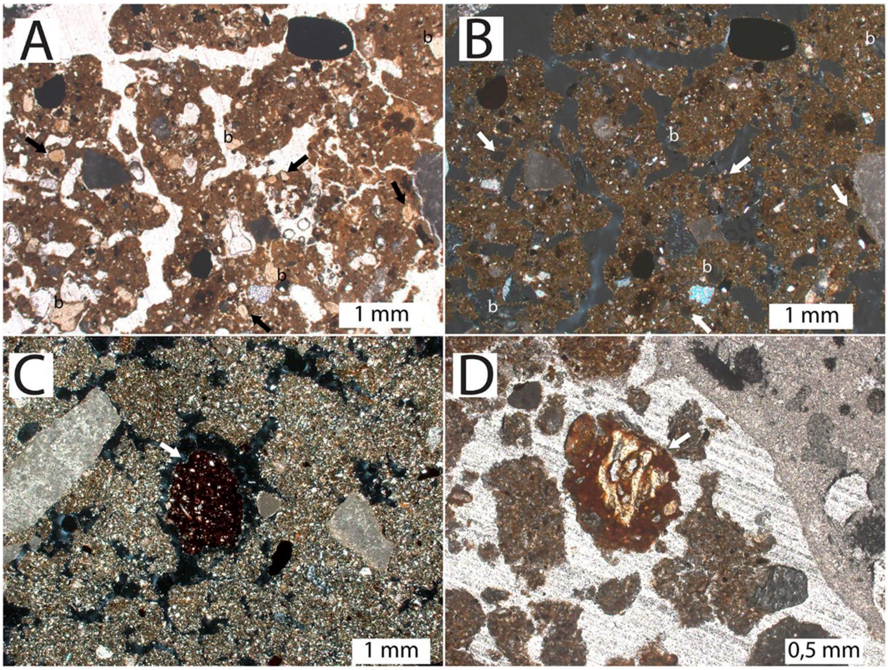

Fig. 7 Schafstall II microphotographs; **A** Open fabric of GH Hf with rounded phosphatics (arrows) and bones (b); SSII-17–6, MU SS4; PPL. **B** Same with **A** but in XPL. **C** MU SS5; Reworked clay-rich aggregate in a calcitic crystallitic matrix dominated by loess. **D** MU SS5; The clay-rich aggregates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

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 suggest a more "primary" process of loess deposition, most likely reflecting aeolian input. Nevertheless, the inclusion of clay-rich aggregates in the coarse fraction, some of which include bones (Fig. 7C and D), might suggest the input of soil material from the surrounding slopes.

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 a loessy coarse component dominated by quartz silt and sand. This deposit is entirely geogenic as it lacks phosphatic aggregates and bones and records a transition to more humid conditions.

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. 8A and B). 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,

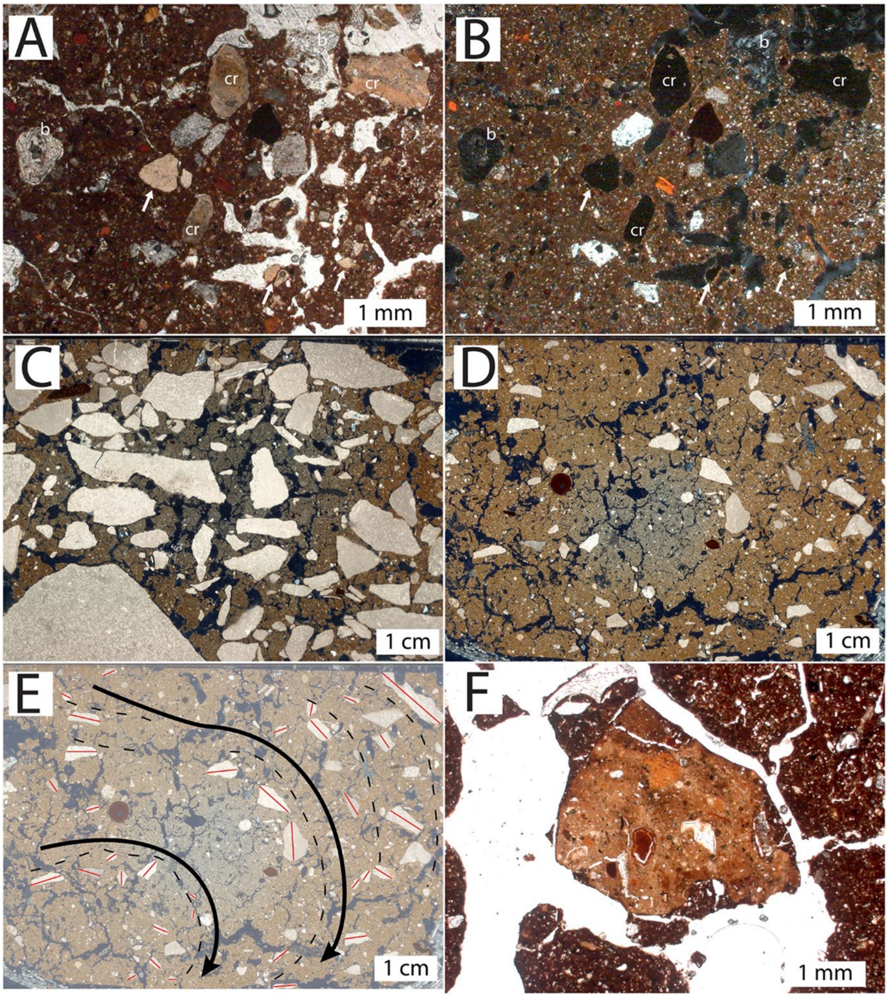

Fig. 8 Photomicrographs from Fetzershaldenhöhle. **A** MU FH1; note the abundance of biogenic components like bones (b), phosphatic grains (arrows), and carnivore coprolites (cr); PPL. **B** Same with **A** but in XPL. **C** MU FH2. Abundant limestone gravels, with an angular shape and moderate orientation, 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

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, but their angular shape demonstrates limited movement 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 E). 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).

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 characterized by a strongly expressed granostriated or circular striated b-fabric (Fig. 9A). The chaotic 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

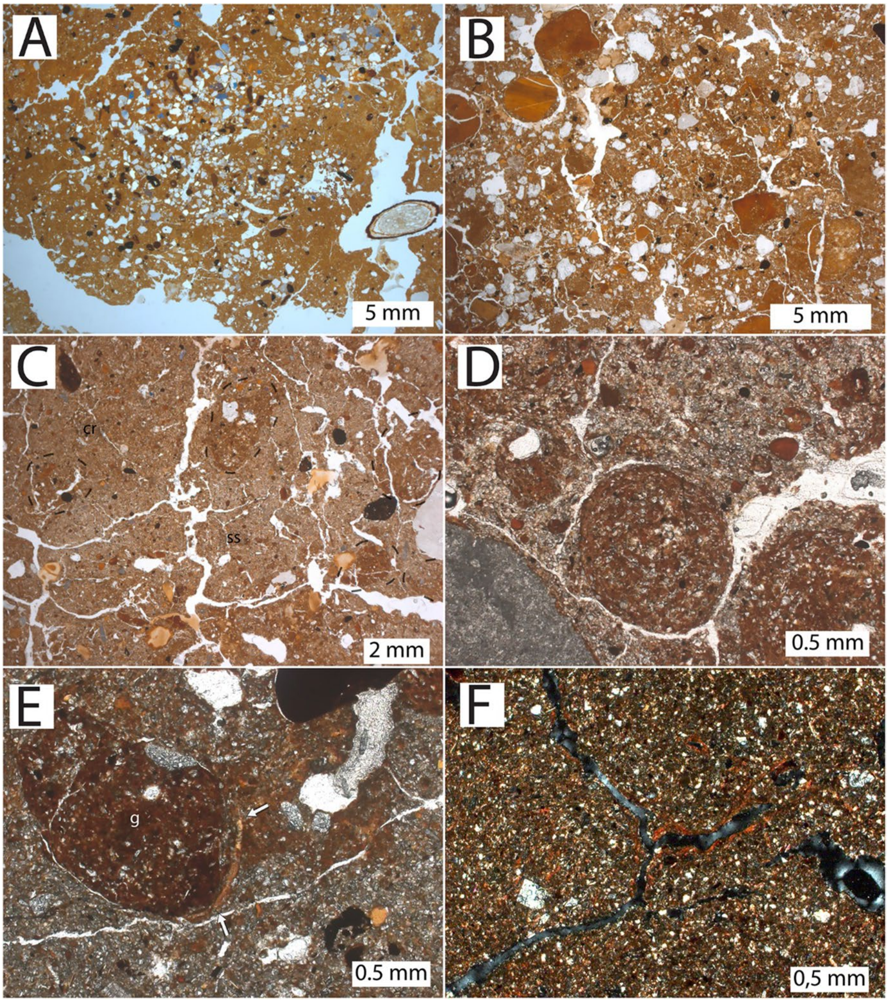

Fig. 9 Microphotographs from Lindenhöhle. **A** MU LH1; iron-rich clays with clast-supported domains made of quartz sand (center of figure); PPL. **B** MU LH2; notice coarser grain size in comparison to MU LH1 (Fig. 9A); PPL. **C** MU LH3; reddish clay-rich sediment (cr) mixed with a lossier sediment (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

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, which corresponds to GH 2, sample LH-13–3. MU LH4 is a homogeneous geogenic deposit without redeposited 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).

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. 10), 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.

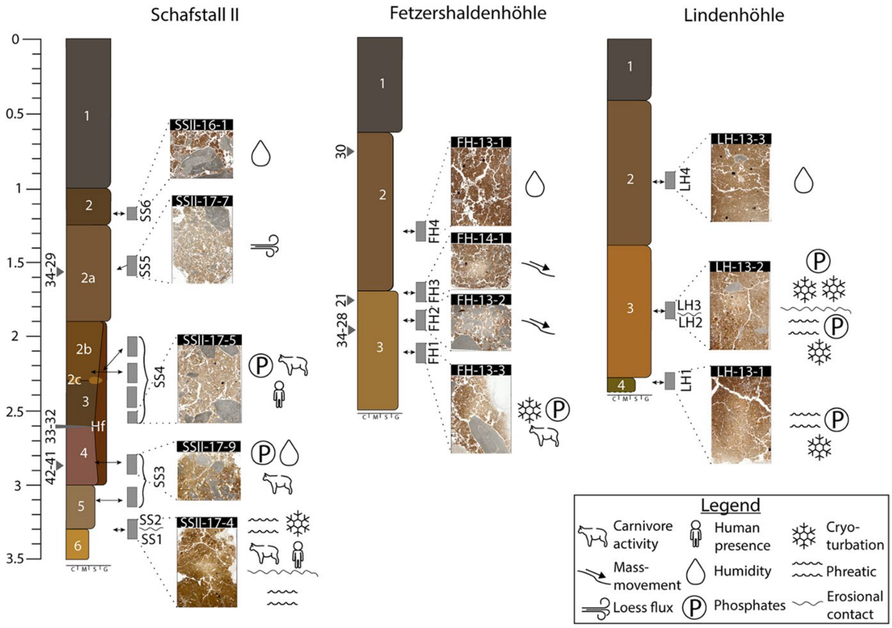

Fig. 10 Summary stratigraphic logs of the excavated sequences from Schafstall II, Fetzershaldenhöhle, and Lindenhöhle. To the right of each log location of micromorphology samples followed by MU classification and main microstratigraphic features. To the left of the logs from Schafstall II and Fetzershaldenhöhle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

Synthesis of Site Formation Processes and Palaeoclimatic Implications

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 Paleolithic, 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 (Goldberg et al., 2019; Miller, 2015), dated to around 94–43 ka BP (Conard et al., 2019; Richard et al., 2019), and the Middle Paleolithic layers at Hohle Fels (Miller, 2015), dated to 62,5 ± 4 ka BP for the lowest layer (Conard et al., 2021).

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 Paleolithic. 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 appear 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, phosphatization/decalcification, and cementation (Miller, 2015). The wet and moist conditions identified in MU SS3 probably characterized the terminal Middle Paleolithic 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 Paleolithic is not exclusive to the Lauchert Valley, but they are also reported in the Ach Valley at the sites of Hohle Fels and Geißenklösterle (Goldberg et al., 2019; Miller, 2015). In this context, the transition from the Middle Paleolithic 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 Paleolithic (Rhodes et al., 2018; Riehl et al., 2015; Ziegler, 2019) and the Gravettian (Krönneck, 2012; Münzel, 2019; Münzel et al., 2011; Riehl et al., 2015) in the Swabian Jura, corroborated also by micromorphological analysis (Goldberg et al., 2019; Miller, 2015).

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 probably 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 is missing from Schafstall II, but 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 Lone 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.

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 redeposited and 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 specific animal activities. 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 Paleolithic to the Gravettian.

Low-Density Sites and Paleolithic 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 Paleolithic (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 do not always reflect geological processes but rather hominin choices.

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 choices 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 processes that we identified in Schafstall II could have reworked partially individual deposits (e.g., GH 5), 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 archaeological assemblages 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 and 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 (Goldberg et al., 2003; Miller, 2015; Marcazzan et al., 2022; Schiegl et al., 2003).
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 mass movement and probably roof collapse event that was documented in the upper part of GH 3 in Fetzershaldenhöhle.
3) The increased presence of fauna, including carnivores.

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

Interaction Between Animals and Humans in Caves and Rockshelters

The antagonistic relationship between bears, 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., 2015a, b) especially during the Middle Paleolithic. More intense human occupation in the region during the Upper Paleolithic (Conard, 2011) led to increased confrontation between humans and animals (Camarós et al., 2016; Kitagawa et al., 2012; Münzel & Conard, 2004a, b) 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 Paleolithic is associated with a decrease in the amount of faunal material accumulated in the caves by carnivores (Camarós et al., 2016; Conard, 2011), demonstrating that the role of carnivores as depositional agents is influenced by the settlement patterns of the Paleolithic groups.

Monitoring bear/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. 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 intact coprolites found in deposits that are less influenced by processes that break down materials, like 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; Goldberg et al., 2003; Karkanas et al., 2000; Shahack-Gross et al., 2004).

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 Paleolithic 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 (Kitagawa et al., 2012; Münzel, 2019; Münzel & Conard, 2004a; Romandini et al., 2018). 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).

In the Swabian Jura, phosphate grains and phosphatized sediments are observed throughout all the cave sequences examined with micromorphology (Barbieri & Miller, 2019; Goldberg et al., 2003, 2019; Miller, 2015), but their distribution varies throughout the Paleolithic. In more detail, even though secondary phosphates and phosphatized loess are found in both the low-density Middle Paleolithic and the higher-density Upper Paleolithic deposits in Hohle Fels and Geißenklösterle (Miller, 2015), as well as Hohlenstein-Stadel (Barbieri, 2019; Barbieri & Miller, 2019), primary phosphates in the form of carnivore coprolites are more abundant in the Middle Paleolithic. 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 animal activity in caves. In the case of carnivore coprolites, these could also demonstrate alternating hominin occupation and carnivore denning, based on the premise that humans and carnivores do not occupy cave spaces simultaneously (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 (Miller, 2015; Shahack-Gross et al., 2004). In contrast, at least in the case of the Swabian sites, the increased presence of carnivore coprolites during the Middle Paleolithic 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 (Barbieri, 2019; 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, Fetzershaldenhöhle, and Lindenhöhle. 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.

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).

Exploring Cave Use and Find Densities in the Swabian Jura

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 Paleolithic to early Gravettian deposits, which might have resulted in the mixing between the frequent bear/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-bear/carnivore activities, have been suggested for the occurrence of Paleolithic artifacts in carnivore dens outside of the Swabian Jura (Morley, 2017; Sanchis et al., 2019; Villa & Soressi, 2000). 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. Among the studied sites, Schafstall II and Fetzershaldenhöhle have low artifact densities 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. Lindenhöhle, on the other hand, has an almost exclusive geogenic sequence with minor biogenic input, indicating that neither humans nor carnivores selected this site for occupation. To explore why these sites are poorer in archaeological finds, we need to examine their contextual differences.

The low-find densities associated with Upper Paleolithic deposits in Schafstall II appear to be consistent with existing archaeological data from the other sites of the Lauchert Valley. Specifically, based on the published accounts from the old excavations from Annakapellenhöhle, Göpfelstein, and Nikolaushöhle, we can surmise that the Lauchert Valley might have been more populated during the Middle Paleolithic than the Upper Paleolithic (Peters, 1936a, b, 1939; Peters & Paret, 1949; Peters & Reith, 1936; Toniato, 2021). Moreover, Schafstall II is not the only cave in the Lauchert Valley with evidence of animal denning, as Göpfelstein has been associated with hyena denning during the Middle Paleolithic and Nikolaushöhle with bear denning during the Upper Paleolithic (Peters, 1936a). Overall, these data suggest that Lauchert Valley was not the focus of human activities during the Upper Paleolithic, with sites like Schafstall II used sparsely, probably as short-term hunting stations (Toniato, in preparation).

In contrast to the limited human presence in the Lauchert Valley, Fetzershaldenhöhle and Lindenhöhle are both located in the Lone Valley, which documents rich human occupation during both the Middle Paleolithic and the Aurignacian. The low-density record found in Fetzershaldenhöhle and the lack of anthropogenic input in Lindenhöhle could have been related to their confined cave spaces (see Online Resource Fig. 1A and 1B), which probably did not foster long-term residential use but rather short-term visits. Moreover, Fetzershaldenhöhle constitutes one of the few caves in the eastern part of the Swabian Jura occupied almost exclusively by carnivores. The few recovered artifacts from Fetzershaldenhöhle, however, demonstrate that the short-term visits into the cave involved the processing of carcasses (Lykoudi, 2018), activities utilizing rare organic tools (Conard & Zeidi, 2014; Lykoudi, 2018), and a piece of worked ivory, most probably a part of a figurine or jewelry (Conard & Zeidi, 2014). Surprisingly, a nearby cave in the Lone Valley, Hohlenstein-Stadel, has also been occupied mostly by carnivores and cave bears during the Upper Paleolithic (Barbieri, 2019; Kind, 2019a), while it also provides one of the best examples of figurative art in the Swabian Jura, the “Lion Man” (Löwenmensch) (Kind et al., 2014). The examples from Fetzershaldenhöhle and Hohlenstein-Stadel might indicate that some caves in the Lone Valley were used for more infrequent and special tasks in comparison to the caves in the Ach Valley. Regarding Lindenhöhle, the evidence of cold conditions preserved at GH 3 and GH 4, although undated, could be related to the absence of anthropogenic input and the limited presence of animal activity found in the cave. Proving this correlation true by future studies could demonstrate that local climatic oscillations impacted the size of carnivore and human populations present in the Lone Valley. Exploring this relationship is especially important for understanding settlement patterns in the Swabian Jura, given that lower population densities have already been suggested for the Lone Valley during the Gravettian (Conard et al., 2012).

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). Higher mobility during the Middle Paleolithic led to sporadic cave use and low-find densities (Conard et al., 2012), with hunter-gatherer groups traversing not only the Ach and Lone Valleys but also the Lauchert Valley. This settlement system seems to change during the Aurignacian and Gravettian, when humans focus their activities on the Ach and Lone Valleys, probably as a result of different subsistence strategies utilizing a seasonal use of caves. The Ach Valley shows higher find densities in comparison to the Lone, especially during the Gravettian (Conard & Moreau, 2004; Moreau, 2010), with repeated occupations during the winter and spring (Münzel & Conard, 2004b). In contrast, 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). The lower find densities in the Lone Valley in comparison to the Ach may reflect also the presence of caves with more ephemeral use, like Fetzershaldenhöhle or Hohlenstein-Stadel, and were probably also influenced by intense erosional processes, particularly affecting Gravettian deposits (Barbieri et al., 2018, 2021). Nevertheless, despite this noisy record, 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).

Methodological Suggestions for Investigating Low-Density Sites in Hunter-Gatherer Contexts

From an ethnographic perspective, an ephemeral use of caves and rockshelters by hunter-gatherer groups that could produce a low-find density record 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 Paleolithic 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 and 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 natural 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). The combination of survey, test-pits, and micromorphology is able to generate a first “layer” of data that assesses regional formation processes and guide research questions for future work. After grasping a basic understanding of the drivers that form a low-density record, it is advisable to apply additional techniques, like remote sensing, coring, or geophysics, which could target specific regional questions, such as landscape erosion or the spatial distribution of artifacts (e.g., Barbieri et al., 2018, 2021).

Conclusions

Paleolithic 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., Conard et al., 2004, 2012; Heydari-Guran et al., 2015; Isaac, 1981; Roebroeks et al., 1992). 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 does 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 Paleolithic 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 almost exclusively geogenic sequence at Lindenhöhle, where biogenic input is much more limited.

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 Paleolithic.

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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Declarations

Conflict of Interest The authors declare no competing interests.

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