Journal of Human Evolution 173 (2022) 103267

Contents lists available at ScienceDirect

Journal of Human Evolution

journal homepage: www.elsevier.com/locate/jhevol

Post-LGM environments and foragers on the move: New data from the lower Altmühl Valley (Franconian Jura, SE Germany)

Alvise Barbieri [a, *], Andreas Maier [b], Tobias Lauer [c, d], Carsten Mischka [e], Merlin Hattermann [e], Thorsten Uthmeier [e]

[a] Interdisciplinary Center for Archaeology and the Evolution of Human Behaviour (ICArEHB), FCHS, University of the Algarve, Campus de Gambelas, 8005-139 Faro, Portugal
[b] Institute of Prehistoric Archaeology, University of Cologne, Bernhard-Feilchenfeld-Str. 11, 50969 Cologne, Germany
[c] Max Planck Institute for Evolutionary Anthropology — Department of Human Evolution, Deutscher Platz 6, 04103 Leipzig, Germany
[d] Terrestrial Sedimentology, Department of Geosciences, University of Tübingen, Schnarrenbergstr. 94-96, 72076 Tübingen, Germany
[e] Institute for Pre- and Protohistory, Friedrich-Alexander-Universität Erlangen-Nürnberg, Kochstrasse 4/18, 91054 Erlangen, Germany

ARTICLE INFO

Article history:
Received 6 December 2021
Accepted 13 September 2022
Available online 26 October 2022

Keywords:
Altmühl Valley
Forager/environment interactions
Magdalenian recolonization
Geoarchaeology
Luminescence dating

ABSTRACT

After the Last Glacial Maximum, the Swabian and Franconian Jura (in SW and SE Germany, respectively) were repopulated by Magdalenian hunter-gatherers within the same communication network. However, while the Magdalenian settlement of the Swabian Jura dates to 17—14 ka cal BP, permanent Magdalenian occupations in the Franconian Jura date to 15—14 ka cal BP. In comparison with its western counterpart, the Franconian Jura was mostly excavated in the early days of archaeological research. Does this different chronology reflect the different history of research? Why did Magdalenian foragers establish permanent occupation in the Franconian Jura nearly 2 millennia after settling in Swabia, despite the fact these regions are only 150 km apart? To address these questions, we reinvestigated two sites in the Altmühl Valley with micromorphology and luminescence dating, namely Felsenhäusl-Kellerhöhle and Klausennische. Our data show that both sites have intact Pleistocene deposits. Among these, we identified sediments dating between 17 and 15 ka that show only rare lithic artifacts and microfeatures indicative of cold and arid conditions. Our work and published data suggest that the steady settlement of Magdalenian foragers in the Altmühl Valley starting 15 ka cal BP coincides with the end of this harsh period and the onset of cool and wetter environments. Data from the Swabian Jura demonstrated that in the Lone Valley, similar environments and Magdalenian occupations commenced earlier, starting 17 ka cal BP. Therefore, we propose that regional environments acted as a barrier against the dispersal of foragers in the Franconian Jura and determined its later Magdalenian occupation. Our research highlighted that different environments, taphonomic processes, and site uses probably coexisted across the German Jura. Therefore, it remains fundamental to expand the multisite data set proposed in this article to further test hypotheses about human/environment interaction in this region.

1. Introduction

1.1. Background

Several studies have demonstrated that paleoenvironmental data from ice cores and ocean drillings can be very useful to contextualize major shifts in human behaviors and genetics, as observed at the European continent between 30 and 20 ka (e.g., Hewitt, 1996; Jochim et al., 1999; Posth et al., 2016; Maier, 2017). While ideal to study global and continental trends, these and similar archives often do not capture the regional variability of past environments (e.g., Müller et al., 2014; Nerudová et al., 2016; Antczak-Orlewska et al., in press). Therefore, correlating archaeological occurrences with these distant paleoenvironmental archives might leave some archaeological questions unanswered. This article focuses on one of these unresolved issues, namely the causes of the late Magdalenian resettlement of the Franconian Jura in Southeastern Germany.

In Central Europe, hunter-gatherer presence during the Last Glacial Maximum (LGM) was sparse, though not completely missing (Terberger and Street, 2002; Barbieri, 2019; Barbieri et al.,

* Corresponding author.
E-mail address: abarbieri@ualg.pt (A. Barbieri).

https://doi.org/10.1016/j.jhevol.2022.103267

2021). During the following climatic amelioration, hunter-gatherers dispersed again into Central Europe. Several works hypothesized that the Magdalenian recolonization originated unidirectionally from Franco-Cantabria (Jochim et al., 1999; Terberger, 2003; Küßner and Terberger, 2006), while others argued for an additional population influx from the east as well as subsequent immigration waves and gradual expansion (e.g., Otte, 1992; Housley et al., 1997; Banks et al., 2008; Verpoorte, 2009; Pasda, 2010; Kozłowski et al., 2012; Maier, 2015).

Radiocarbon data from Southern Germany and its bordering regions (e.g., Bohemia and Switzerland; Valoch, 1996; Svoboda et al., 2002; Reade et al., 2020a) indicate that foragers producing Magdalenian artifacts dispersed through the German Jura following an eastward direction (Maier, 2015). These hunter-gatherers probably entered Southwestern Germany as early as 19 ka cal BP[1] (Pasda, 1998; Maier et al., 2020) and established intensive occupation of the Swabian Jura between 17 and 14 ka cal BP (Conard and Bolus, 2003, 2008; Kind, 2003; Taller, 2014; Taller et al., 2014; Hornauer-Jahnke, 2019; Barbieri et al., 2021; published radiocarbon data are listed in Supplementary Online Material [SOM] Table S1). The earliest though ephemeral evidence of Magdalenian occupation in the neighboring Franconian Jura (some 150 km apart) dates to 16 ka cal BP (Housley et al., 1997; Maier, 2015; Maier et al., 2020), while permanent occupation is documented starting 15 ka cal BP (Maier, 2015; Housley et al., 1997; published radiocarbon data are listed in SOM Table S2). Transport patterns of lithic raw materials show a close-knit relation of the Franconian with the Swabian Jura, but not with any other neighboring region (Maier, 2015: 49). In addition, stone slabs with very similar paintings have been found in Magdalenian sites of the Swabian and Franconian Jura, but not elsewhere (Huber and Floss, 2014; Taller, 2014; Taller et al., 2014; Floss et al., 2015). Based on all these observations, it has been argued that the Magdalenian foragers that visited Swabian and Franconian Jura were part of the same territory-conscious network (Maier, 2015: 49).

Previous studies have correlated the arrival of these foragers with environmental oscillations observed at the continental scale, without explaining the long period (nearly 2 millennia) needed by these foragers to expand their area of permanent occupation from Swabian to Franconian Jura, despite the fact that these regions are only 150 km apart (Taller, 2014; Taller et al., 2014; Maier, 2015). Until recently, new research on this topic was stalled by two issues: 1) paleoenvironmental data coming from Swabian and Franconian archaeological sites were very limited (Taller, 2014; Taller et al., 2014; Maier, 2015). Therefore, it was virtually impossible to explore the potential impact of regional (and micro-) environments on the behaviors of the local Magdalenian foragers; 2) in addition, modern systematic archaeological excavations in the German Jura focused mostly on caves and rock shelters from Swabia (e.g., Hohle Fels, Langmahdhalde, Hohlenstein-Stadel; Conard and Uerpmann, 1998; Conard et al., 1999, 2000, 2002, 2003, 2015, 2018, 2019, 2020; Conard and Malina, 2004, 2005, 2007, 2008, 2010, 2012, 2013, 2014, 2016, 2020; Kind et al., 2014; Conard and Janas, 2018; Kind, 2019). On the contrary, most sites from Franconia were extensively excavated in the early days of Prehistoric research (see next chapter). This made unclear whether the limited occurrence and late chronology of Magdalenian occupations in the Franconia Jura was due to the history of research, or it was indeed representative of the archaeological record of this region (Maier, 2015).

Recent works have opened new possibilities to study the causes of the late eastward expansion of Magdalenian foragers into Franconia. Paleoenvironmental data became available from Magdalenian occupations at two sites located in the Lone Valley of the Swabian Jura, namely Hohlenstein-Stadel (Barbieri and Miller, 2019a; Ziegler, 2019) and Langmahdhalde (Wong et al., 2020a, 2020b). In addition, over the last couple of years, the Institute of Pre- and Protohistory of the Friedrich-Alexander-University Erlangen-Nürnberg has initiated a research program to re-evaluate existing sequences from the lower Altmühl Valley, in the Franconian Jura.

In this article, we present results from this research program, focusing on the micromorphology and preliminary luminescence dating of a cave (Felsenhäusl-Kellerhöhle) and a rock shelter (Klausennische) where previous excavations unearthed rare late Upper Paleolithic materials. The goals of this article are to: (1) verify the occurrence of intact deposits at these sites; and (2) use paleoenvironmental data from these and Swabian contexts to explore the causes for the late eastward expansion of Magdalenian foragers into Franconia.

1.2. Deposits and human occupations dating between the Late Glacial Maximum and Late Glacial in the lower Altmühl Valley, in the Franconian Jura

The German Jura is a mountain range (400–600 m asl) located in Southern Germany, delimited by the Danube Valley to the South, the Neckar drainage and the Franconian Heights to the North, the Black Forest to the West, and the Bavarian Forest to the East (Fig. 1). This region is mainly composed of limestone formations hosting numerous caves and rock shelters, some of which were occupied by humans during the Pleistocene and Holocene. The main geological break in the region is represented by the Nördlinger Ries (NR in Fig. 1a), which is an impact crater of Miocene age (Schmieder et al., 2018). The portions of the Jura located to the West and East from the NR are known as Swabian and Franconian Jura, respectively.

Sesselfelsgrotte (located 25 m above the town of Essing, SG in Fig. 1b) is regarded as the reference site for the lower Altmühl Valley, with a stratigraphic sequence spanning from the Marine Isotope Stage (MIS) 5 to the MIS 1 (Freund, 1998). This rock shelter yielded exceptional finds, including the fossil remains of at least two juvenile and one infant Neanderthals (Rathgeber, 2006). The site was systematically investigated with modern scientific methods by a team of specialists led by G. Freund (Weißmüller, 1995; Freund, 1998; Richter, 2002; Dirian, 2003; Böhner, 2008; Freund and Reisch, 2014; Freund and Richter, 2017). At Sesselfelsgrotte, the transition between Middle and Upper Paleolithic deposits corresponds to a geological break. Gullying and pauses in sedimentation led to the co-occurrence of Middle and middle Upper Paleolithic materials in layers E2 and E3 (Freund, 1998; Böhner, 2008). After a subsequent erosional phase, the Middle Paleolithic deposits were covered with layer D, which exhibits higher loess content in comparison with the rest of the site sequence and no faunal or lithic materials (Freund, 1998). Luminescence methods dated this deposit to 16.2 ± 1.9 and 16.3 ± 1.5 ka (Richter et al., 2000). This sediment was later buried with two distinct archaeological layers (C1 and C2), which appeared separated by a disconformity (Freund, 1998; Dirian, 2003). Both layers exhibited lower loess content, higher amounts of fresh, angular, platy limestone gravel, and Magdalenian materials (Freund, 1998; Dirian, 2003), which included faunal remains dating between 15.5 and 14.5 ka cal BP (Housley et al., 1997; for a critical review see Terberger, 2008; SOM Table S2).

Placed on the right flank of the Altmühl Valley, opposite from Sesselfelsgrotte, Klausenhöhlen is one of the larger and most important cave systems in our study region (KH in Fig. 1b). This complex hosts multiple caves and rock shelters, such as Untere

[1] All radiocarbon ages reported in this article were calibrated with the software OXCal v. 4.4, using the IntCal20 calibration curve.

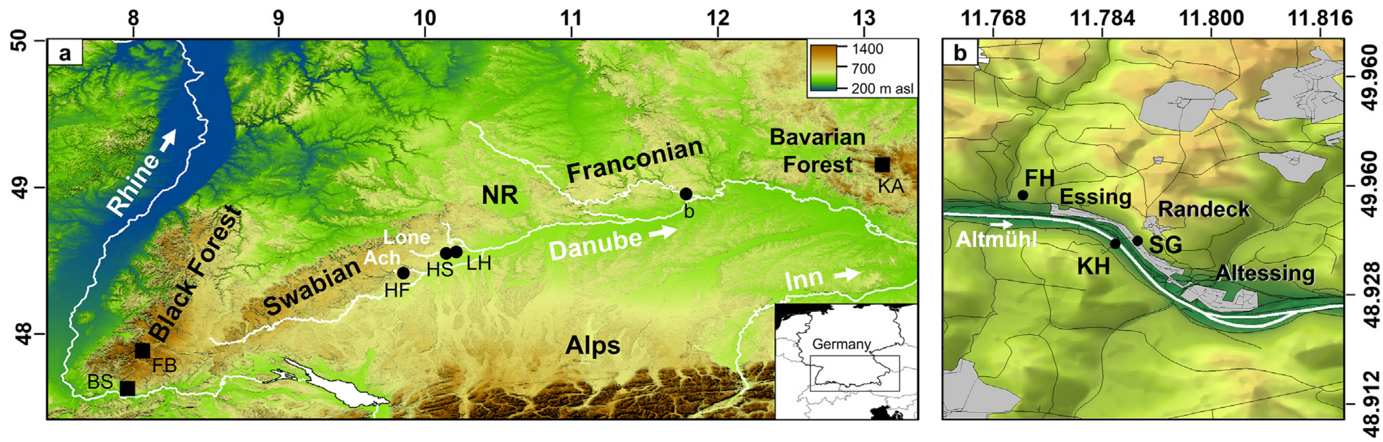

Figure 1. The study region. a) Overview of the German Jura and Nördlinger Ries (NR) in Southern Germany. Black circles indicate archaeological sites: Hohle Fels (HF), Langmahdhalde (LH), Hohlenstein-Stadel (HS), cluster of sites in the Altmühl Valley (b). Black squares depict paleoenvironmental sites: Kleiner Arbersee (KA), Feldberg (FB), Bergsee (BS). b) Overview of main Upper Paleolithic sites with Magdalenian occupations in the lower Altmühl Valley: Felsenhäusl (FH), Klausenhöhle (KH), Sesselfelsgrotte (SG). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

Klause, Klausennische, Mittlere Klause, and Obere Klause (Obermaier and Wernert, 1914). In the 19th century, sites within the Klausenhöhlen were partly dug to accommodate modern structures related to a 'Biergarten' (in English 'beer garden,' an outdoor area adjoining a traditional Southern German tavern where alcohol is served), whereas in the early 20th century, they were systematically excavated by archaeologists with now outdated methods (Birkner, 1936). Published data about these excavations and their findings are very poor (Obermaier and Wernert, 1914; Freund, 1961; Kaulich et al., 1978; Kaulich, 1994). At Obere Klause, Middle Paleolithic sediments were covered by two Magdalenian deposits alternating with sterile layers (Kaulich, 1994). The Magdalenian assemblages were composed of lithic tools, painted limestone rocks (Huber and Floss, 2014; Floss et al., 2015), harpoons, needles, ivory objects, and perforated animal teeth (Kaulich et al., 1978; Kaulich, 1994). Similar findings have been reported from various Magdalenian sites from the Swabian Jura, including Hohle Fels (Huber and Floss, 2014; Taller, 2014; Taller et al., 2014; Floss et al., 2015). Two bones from the Obere Klause Magdalenian assemblages were dated with radiocarbon to 15 and 14 ka cal BP (Housley et al., 1997). At Mittlere Klause, cut in the Middle Paleolithic deposits was a burial, which was dated to 21.9 ka cal BP and represents the oldest fossil of *Homo sapiens* ever recovered in Germany, although a re-dating is urgently needed (Street et al., 2006). This inhumation was covered with sediments exhibiting lithic tools that can be assigned either to the Magdalenian or to the Gravettian (Beck et al., 2006). Although a radiocarbon date from this deposit gave an age of 16 ka cal BP (Housley et al., 1997; SOM Table S2), which falls into the range of Magdalenian dates, the hypothesis of a Gravettian component in this assemblage cannot be excluded. Re-evaluation of the lithic artifacts from this deposit yielded a Font-Robert-type point and a radiocarbon date of 29 ka cal BP on a worked bone fragment (Housley et al., 1997; Beck et al., 2006; SOM Table S2). The fact that Gravettian and Magdalenian materials appear to co-occur in the same deposit might be due to the poor excavation methods used at the time, or it might result from postdepositional disturbance (Kaulich, 1994). Stratigraphic data from Klausennische are limited to a very brief description, reporting a sequence composed of (bottom to top) a sterile red clay, two rich Middle Paleolithic deposits, a layer possibly dating to the Upper Paleolithic, and a deposit bearing Neolithic materials (Obermaier and Wernert, 1914; Birkner, 1936). The Middle Paleolithic finds included backed bifacial knives of Klausennische type, flat handaxes termed 'Faustkeilblätter' by the excavators, and numerous Keilmesser knives (Obermaier and Wernert, 1914; Bosinski, 1967). Later analysis (Kolobova et al., 2019) confirmed the Micoquian status of the Middle Paleolithic finds. The excavation of the Middle Paleolithic deposits unearthed also faunal remains, charcoal fragments, burnt bones, and a human tooth of a Neanderthal infant, which was held by private collectors and eventually lost (Müller-Beck, 1957; Schoch, 1973; Rathgeber, 2006). More recently, renewed excavations at the site focused on clarifying the stratigraphic sequence and dating the find-bearing sediments (Uthmeier et al., 2019).

Felsenhäusl is a cave system located on the left flank of the Altmühl Valley, 3.6 km to the West from Sesselfelsgrotte (Hattermann et al., 2019; FH in Fig. 1b). This karst system is composed of three separate cavities, from which sediments were nearly entirely removed by the private owner of the site. Of the three caves, only at Felsenhäusl-Kellerhöhle, archaeological material was recovered. The site was excavated in the year 2000 by removing spits of 30 cm and separating the finds accordingly to these artificial levels (Kaulich and Weißmüller, 2003; Hattermann et al., 2019). In the light of these findings, the Bavarian Cultural Heritage Office prohibited any further excavation at this site. Archaeological investigations carried out by Kaulich and Weißmüller (2003) documented a profile exhibiting stratified sediments at the back of the cave, which they interpreted as a remnant from the previous excavation. Recent re-evaluation of the lithic artifacts (Hattermann et al., 2019) testified the low stratigraphic reliability of the spits distinguished during the unauthorized excavations (Fig. 2). It is assumed that the bulk of the material was unearthed in the wider part of the cavity toward the cave entrance and underwent severe anthropogenic disturbances due to a later use of the cave in historical times. The lithic analysis identified diagnostic tools from the Micoquian and artifacts comparable with the Magdalenian assemblage from Sesselfelsgrotte (Hattermann et al., 2019).

This recent study was part of a broader research program led by the Institute of Pre- and Protohistory of the Friedrich-Alexander-University Erlangen-Nürnberg to re-evaluate existing sequences from the lower Altmühl Valley. Within this wider research program, our work has focused on the karstic system of Felsenhäusl and Klausenhöhlen. We report our geoarchaeological and dating results from previously unknown Pleistocene

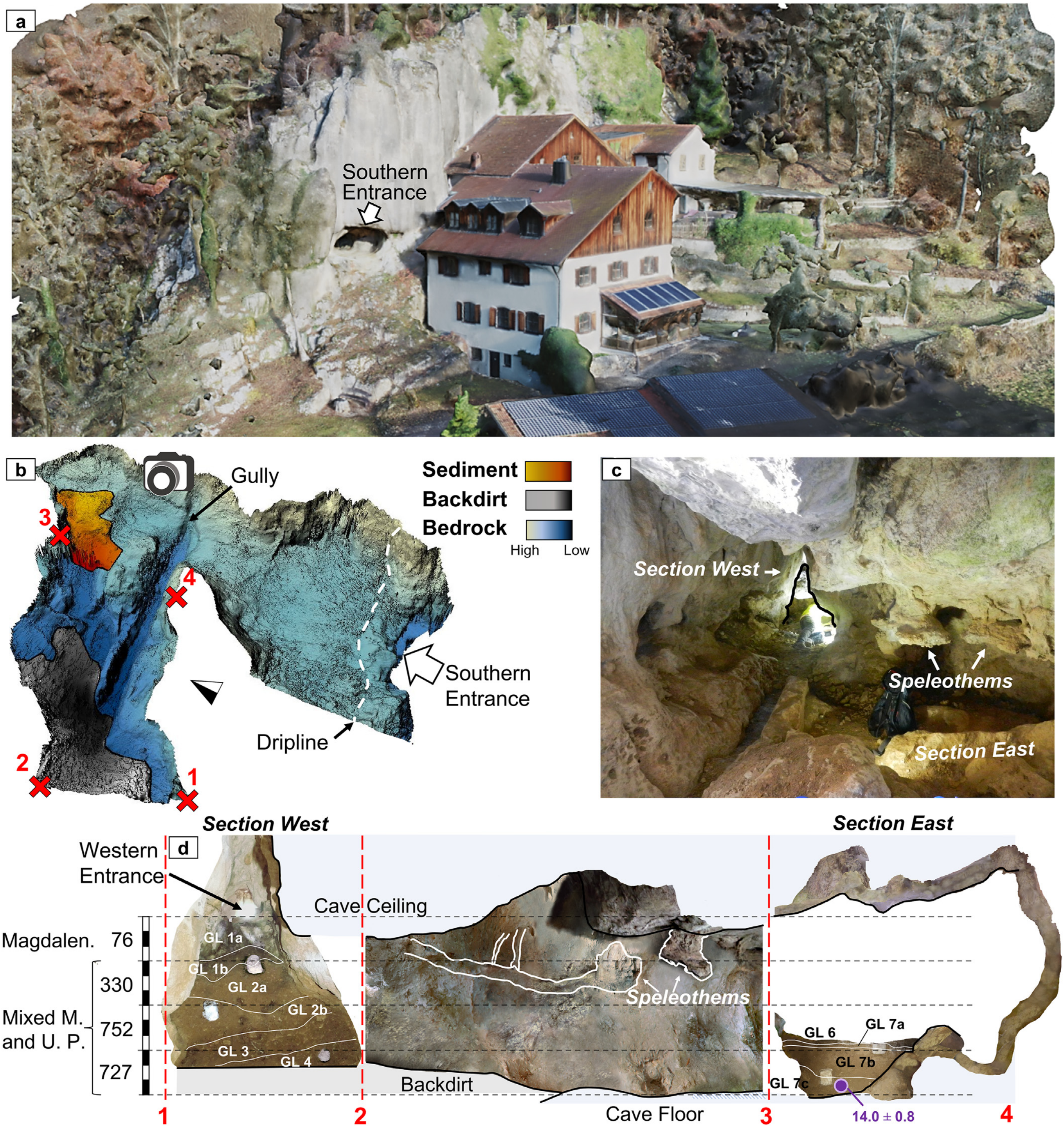

Figure 2. Felsenhäusl-Kellerhöhle Cave. a) 3D model of Felsenhäusl with the Southern (main) entrance to the Felsenhäusl-Kellerhöhle. b) Topography of the ground surface inside the cave. The camera symbol indicates the location from which panel c was taken. c) Photo showing sediment remnants within the cave: Section East and speleothem formations in the foreground, and Section West (during sampling) in the background. d) A composite photogrammetric image depicting the main sediment remnants preserved inside the cave, namely Section West, Section East, and speleothem formations along the Northern cave wall. Note the small opening on top of Section West, which represents the second entrance to the site. The geological layers (GLs) mentioned in the text are labeled on the image. White rectangles show the location of block samples for micromorphological analysis. The luminescence date Fe-Häusl-1 is depicted in purple. The dashed lines indicate the approximate location of the 30 cm deep spits, which were previously excavated by the owner of the site. On the left of Section West, we report the amount of lithic artifacts from each spit and their archaeological attribution, as proposed in Hattermann et al. (2019). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

sediment remnants from Felsenhäusl-Kellerhöhle and Klausennische, which allow us to investigate the relation between human occupations and environmental changes across the German Jura.

2. Material and methods

Felsenhäusl-Kellerhöhle is located some 20 m above the valley bottom and consists of a 6 m long, 2.4 m wide, and 1.2 m high phreatic tube (Fig. 2), which exhibits two separate entrances. The main one is 1.4 m high and 2 m wide, opens toward South, and is accessed through a small (ca. 3 m^2) limestone terrace. The second entrance faces West, measures only 0.3 m in width and 0.2 m in height, and opens directly on the steep (ca. 50°) hillside. Excavations conducted by the private owner of the site reached the bedrock in many areas within the cave, revealing the uneven limestone floor.

Klausennische is a small rock shelter, measuring 18 m in width, 5 m in length, and 2.6 m in height (Figs. 3 and 4). The site rests at 28 m above the valley bottom, faces North-East, and opens on an artificial terrace stretching over an area of some 20 × 10 m. This landform was created in the 19th century by truncating the Pleistocene sequence that originally filled the site, which was subsequently excavated in the early 20th century by Obermaier, Wernert, and Fraunholz (Obermaier, 1904; Obermaier and Wernert, 1914, 1929; Obermaier and Fraunholz, 1926). Renewed archaeological investigations at the site commenced in 2019 (Uthmeier et al., 2019). The excavation area was divided into forty 1 × 1 m squares, each of them was subdivided into four quadrants (a = North-West; b = North-East; c = South-West; d = South-East) measuring 25 × 25 cm (Figs. 3 and 4). Deposits were dug with spits of 5 cm respecting the morphology of sedimentary contacts. The position of finds larger than two centimeters was recorded with a total station, while the location of smaller finds was recorded based on the excavation spit and the subsquare. After the excavation, sediments were wet sieved in the field.

At both Felsenhäusl-Kellerhöhle and Klausennische, sediment profiles were photographed, hand drawn, and recorded with a total station. 3D models of Felsenhäusl-Kellerhöhle and Klausennische were realized with structure from motion methods with the software Agisoft Metashape. Within each sediment profile, we distinguished separate geological layers (GL) and sublayers (e.g., a, b, etc.) based on lithological properties. The numbering of the layers

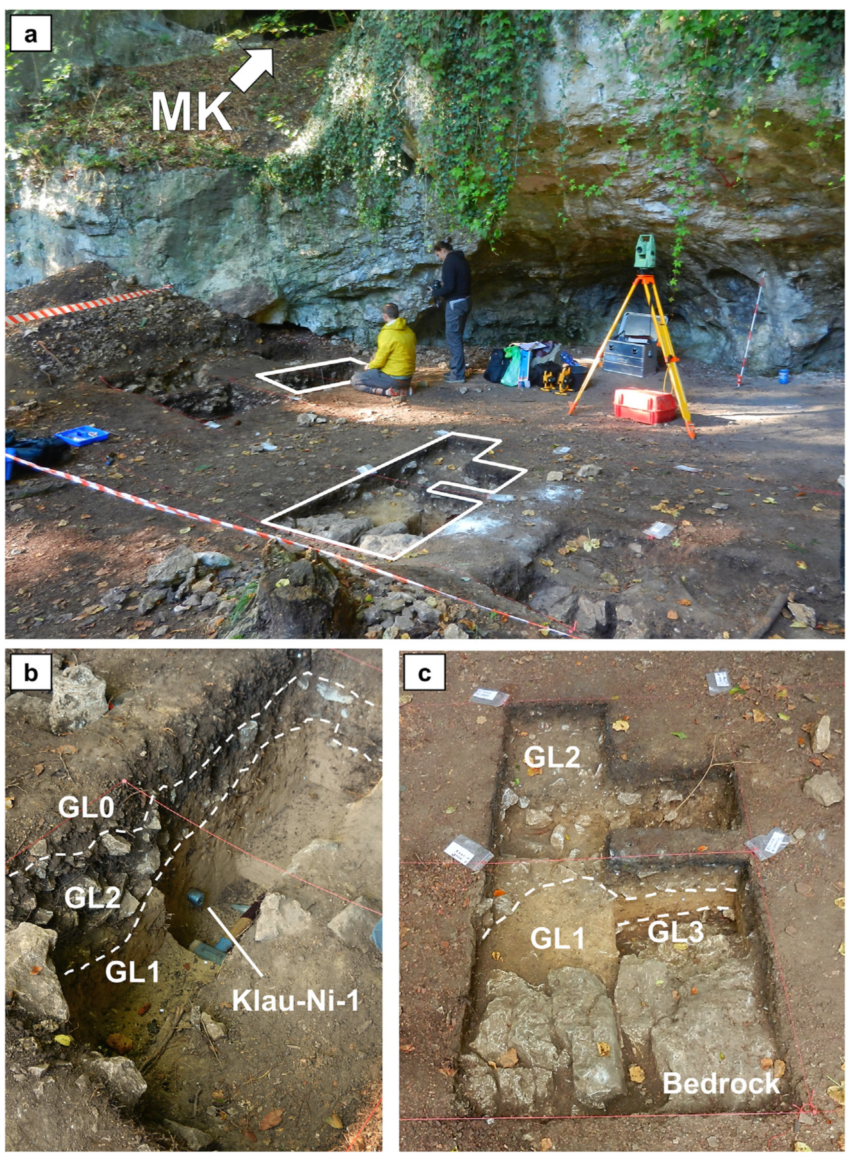

Figure 3. New excavations at Klausennische. a) Photo of Klausennische looking toward South-West. One of the main entrances to Mittlere Klause is indicated by MK. White rectangles to the left and right depict excavation areas photographed in panels b and c, respectively. b) Excavation of subsquares 1007/1992 b and d, main lithological units, and luminescence sample (Klau-Ni-1) are labeled in white. c) Excavation of squares E 1004/N 1995 (top) and E 1004/N 1995 (bottom). Main lithological units are labeled in white. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

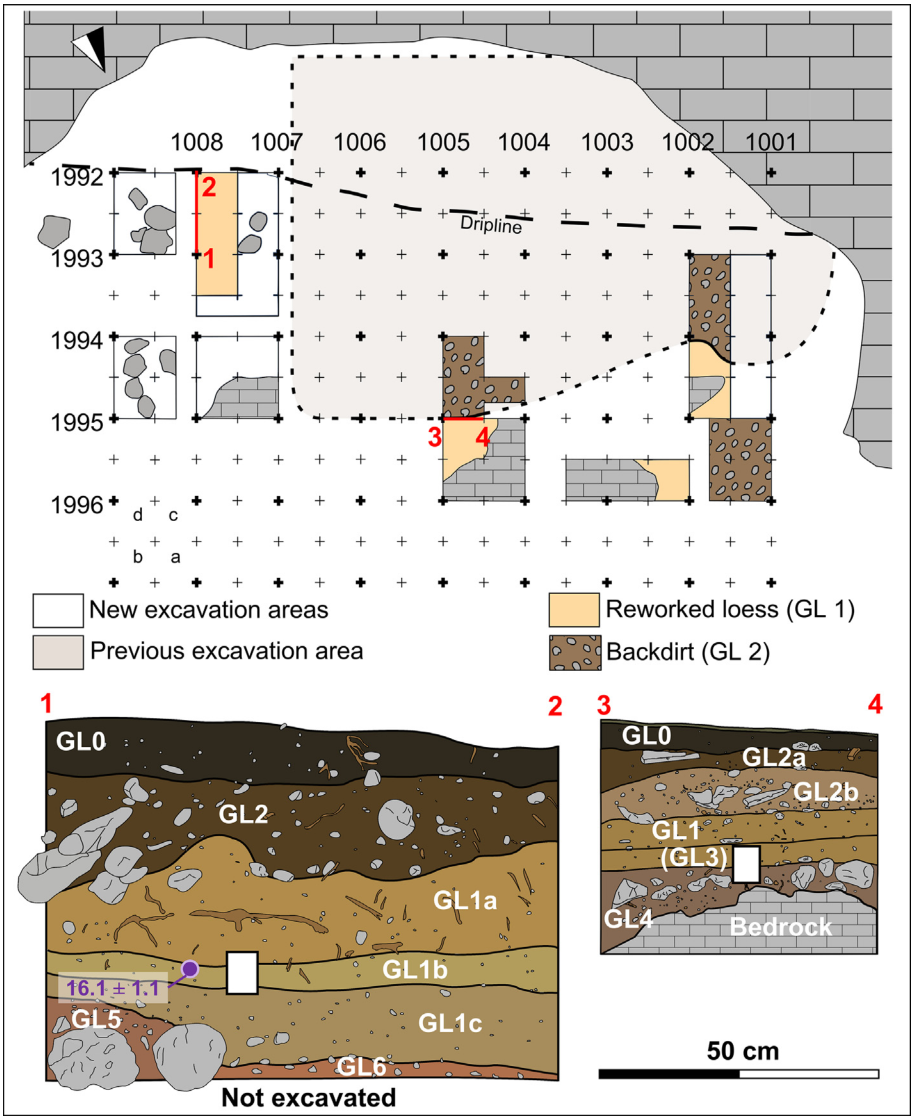

Figure 4. New excavations at Klausennische. Sketch map of the new excavation squares depicting the spatial distribution of geological layer (GL) 1 and GL 2 at 30 cm of depth, which enables us to delimit the likely location of the areas excavated in the early 20th century. Lithological units are labeled in white, micromorphological block samples are indicated with white rectangles while the luminescence sample Klau-Ni-1 with a purple circle. Excavation sub-squares are indicated with the letters "a", "b", "c", "d ". Abbreviations: 1–2 = East profile from E 1007/N 1992d and b; 3–4 = south profile from E 1004/N 1995d. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

indicates the succession in which they were identified during the excavations and is therefore independent from the actual stratigraphic sequence. The lithological properties used to distinguish between GLs included depth, transition to the next lower sediment (Fitzpatrick, 1980), and amount of coarse (>2 mm) and fine fraction (<2 mm; Chilingar et al., 1967). For the coarse fraction, we described color, composition, frequency (Chilingar et al., 1967), size (ISO 14688-1:2002 standard), shape (Zingg, 1935), roundness (Powers, 1953), sorting (Stoops, 2021: 57), and orientation. For the fine fraction, we reported Munsell color and grain size (Vos et al., 2016).

Micromorphology is the microscopy study of undisturbed soil and sediment samples (Stoops, 2021). This technique is regarded as a valuable method to reconstruct site formation processes as well as extract paleoenvironmental information from sequences preserved within cave and open-air sites (Goldberg, 1979; Catt, 1991; Kemp, 1999). Details about sample preparation can be found in SOM S1. A total of 9 thin sections (50 × 75 mm, 30 μm in thickness; Figs. 5–10) were analyzed and described using a petrographic microscope in plane polarized (PPL), crossed polarized (XPL), and reflected fluorescence light (FL), following terminology and protocols developed by Stoops (2021).

To get insights into the timing of sediment burial, luminescence dating (Aitken, 1998) was applied to one sample from Felsenhäusl-Kellerhöhle (Fe-Häusel-1 from GL 7c; Fig. 2) and one sample from Klausennische (Klau-Ni-1 from GL 1b; Figs. 3 and 4). Sample preparation and luminescence measurements were conducted under subdued red light at the Department of Human Evolution at the Max Planck Institute for Evolutionary Anthropology in Leipzig (information about sample pretreatment and measurement can be found in SOM S2. Representative decay curve and dose-response curve are displayed in SOM Figs. S1 and S2). To obtain the equivalent dose value, 9 aliquots were measured per sample with the post-infrared-infrared (pIRIR225) approach (more details in SOM S2). The low number of aliquots is explained by the usage of fine grain polyminerals, with thousands of grains

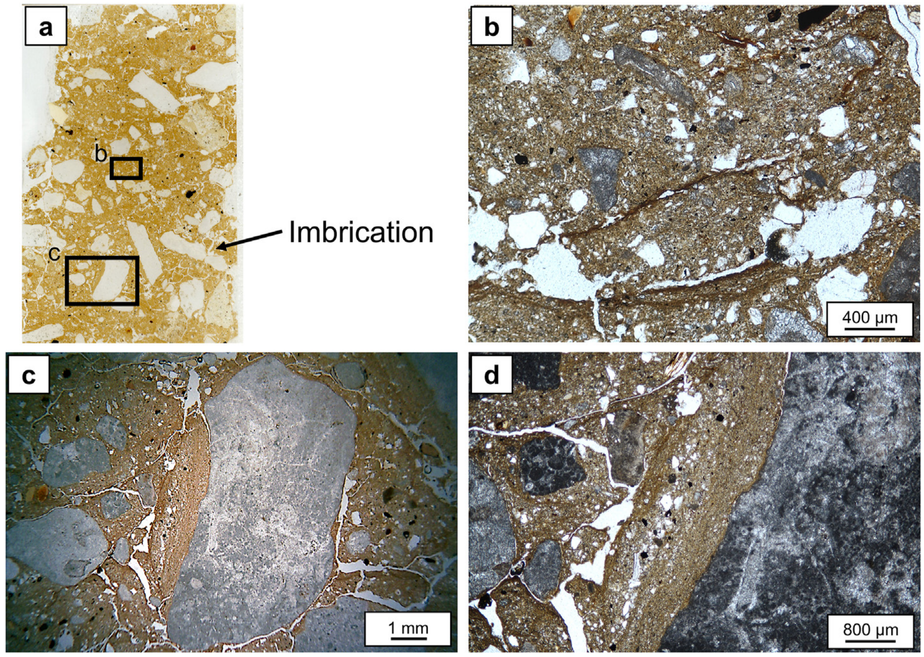

Figure 5. Cryogenic features from geological layer (GL) 4 in Felsenhäusl-Kellerhöhle. a) Scan of thin section FH-4 from GL 4, note the imbrication of limestone gravel in the lower half of the slide. b) Intercalation of clay and silt around straight planes (in plane polarized light [PPL]). c) Fine gravel of limestone showing compound and laminated coating of silt (photomicrograph taken in PPL). d) Detail from panel b (PPL). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

per disc (dense distribution of the equivalent dose [De]). The discs were fully covered with grains (8 mm in average). Consequently, the obtained De-scattering and overdispersion is very low (10% for sample Klau-Ni-1 and 2% for sample Fe-Häusel-1). The calculation of the final De is therefore based on the evaluation of the arithmetic mean including its standard error. All measured aliquots fulfilled the rejection criteria and the recycling ratio deviated always <10% from unity. Table 1 displays an overview of the obtained nuclide concentrations as well as the luminescence dating results.

3. Results

3.1. Geoarchaeological results from Felsenhäusl-Kellerhöhle

Detected sediment remnants The largest sediment remnant preserved at the site consists of a 100 cm deep and 90 cm wide sequence that partly fills the western opening (Section West in Fig. 2). This remnant (from here on 'Section West') was first reported by Kaulich and Weißmüller (2003). In addition to these intact deposits, previous works (Hattermann et al., 2019) identified a 40 cm deep and 80 cm wide exposure ('Section East'), which is trapped within a depression of the bedrock roughly in the middle of the cave (Fig. 2). Last, along the northern cave wall, cemented sediments and speleothem formations, which likely capped the original infilling of the cave, were identified (Hattermann et al., 2019; Fig. 2). Sections East and West were sampled for micromorphological analysis, while one luminescence date was performed on GL 7 in Section East.

Some lithological data were already published in Hattermann et al. (2019). Here we summarize them to provide context for the micromorphological results. Detailed description of the micromorphological samples can be found in SOM Table S3. Data are presented in stratigraphic order, bottom to top. Layers with similar lithological properties and comparable stratigraphic position are presented together.

Geological layer 4 in Section West Kaulich and Weißmüller (2003) previously reported a separate and distinct sediment above the limestone bedrock and below the deposit that we label GL 4. We could not access this lower deposit because this part of the cave was likely refilled before our investigations and new archaeological excavations at this site have been prohibited by the Bavarian Cultural Heritage Office (Hattermann et al., 2019). Hence, GL 4 is the lowermost sediment we documented in Section West, between 90 and 100 cm of depth (Fig. 2).

GL 4 is composed of moderately sorted, triaxial to equiaxial, subrounded to subangular, moderately weathered, fine to medium gravel-sized fragments of limestone and speleothems embedded in yellowish brown (10 YR 4/4) reworked loess. Under the microscope, coarser components appear weakly imbricated (Fig. 5a) and coated with compounded layers of clay, silt, and sand from the groundmass (Fig. 5c, d). Thin section analysis also revealed the presence of up to fine gravel-sized bone fragments. Most of them appear fresh (Fig. 6a), a few are calcined (Fig. 6b), while evidence of apatite dissolution and calcite replacement is very rare (Fig. 6c). We also observed rare, up to fine gravel-sized, elongated, angular chert fragments, which might correspond to chips of lithic artifacts (Angelucci, 2010; SOM Fig. S3a). Charcoal fragments, grains of phosphatized loess (Miller, 2015; Barbieri, 2019), and carnivore coprolites are very rare (Horwitz and Goldberg, 1989; Sanz et al., 2016; SOM Fig. S4a). Under the microscope, the reworked loess that supports the coarser fraction is organized in discontinuous, horizontal, wavy, graded laminations (Fig. 5b).

GL 3 in Section West The upper contact of GL 4 is clear and smooth. On top of it, we documented a 20-cm-thick layer rich in unsorted, fine to coarse, subangular to subrounded, triaxial limestone fragments embedded in a yellowish brown (10 YR 5/4) silty clay/clayey silty matrix (GL 3 in Fig. 2). This sediment was not sampled for micromorphological analysis due to its coarse grain size.

GL 2 in Section West and GL 7 in Section East The upper boundary of GL 3 is delimited by a sharp and wavy contact with a 40-cm-thick

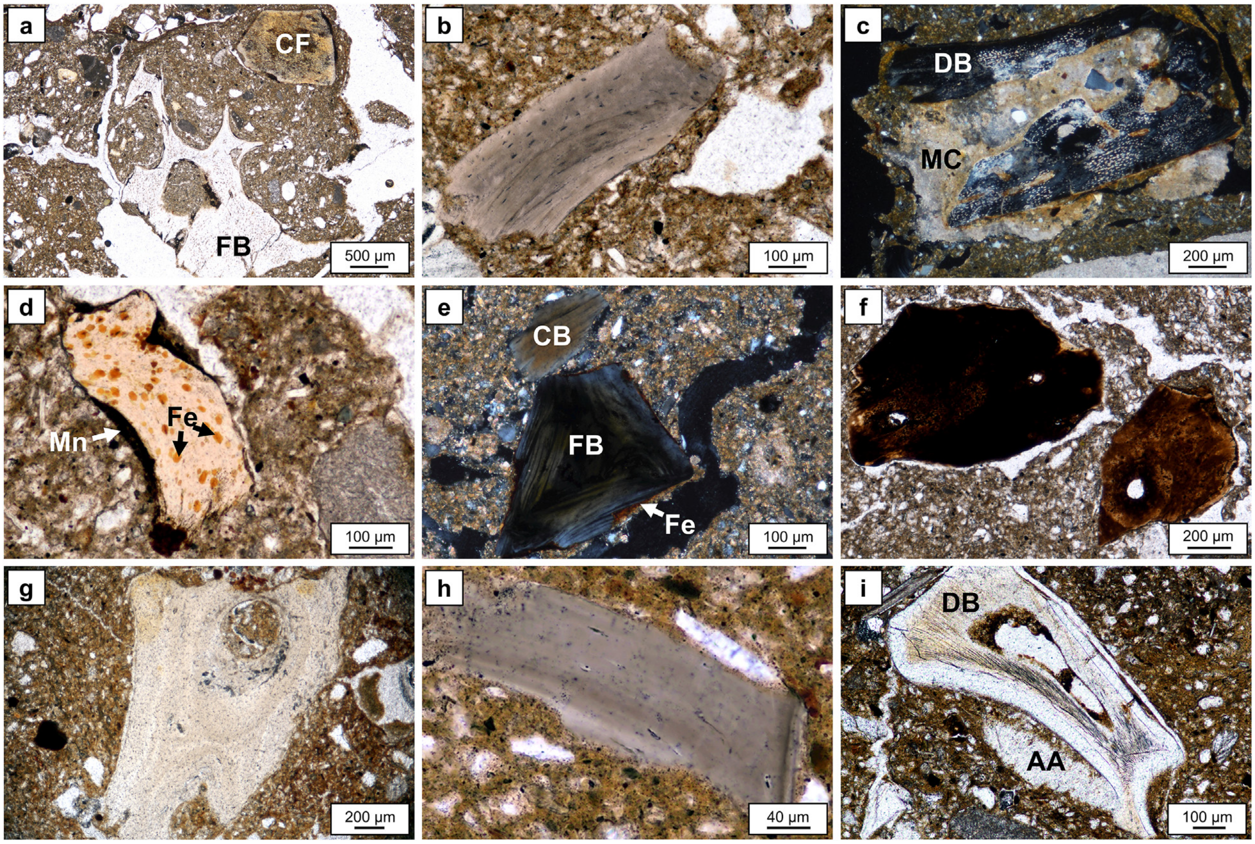

Figure 6. Mixed faunal assemblages from Felsenhäusl-Kellerhöhle and Klausennische. a–c) Photomicrographs from geological layer (GL) 4, Felsenhäusl-Kellerhöhle: a) coprolite fragment (CF) lying next to a fresh bone (FB; photomicrograph taken in plane polarized light [PPL]); b) calcined bone (as shown by the light grey color in PPL); c) micritic calcite (MC) replacing dissolving bone fragment (DB; in crossed polarized light [XPL]). d–f) Photomicrographs from GL 2b, Felsenhäusl-Kellerhöhle: d) bone fragment showing iron impregnations (Fe) and iron-manganese coating (Mn; PPL); e) possibly calcined bone fragment (CB; in XPL) lying next to fresher bone fragment (FB) coated with iron-oxides (Fe); f) bone fragments possibly heated (PPL). g–i) Photomicrographs from GL 4, Klausennische: g) fresh bone (PPL); h) calcined bone (PPL); i) bone (DB) dissolving into amorphous apatite (AA; XPL). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

deposit (GL 2 in Fig. 2) made from reddish brown to brown clayey silt (70%) and rare sorted, subangular, fine gravel of limestone (30%). From Section East, we reported a sediment (GL 7 in Fig. 2) showing lithology similar to GL 2, and elevation and stratigraphic position comparable to the lower part of GL 2.

Thin section analysis showed that GL 2 and GL 7 are composed of reworked loess. Within these units, we identified sedimentary breaks. The lower part of GL 2 (GL 2b) shows rare, immature, limestone fragments delimiting sedimentary surfaces (Fig. 7a). Similarly, GL 7 shows layers exhibiting different degrees of bioturbation, which might reflect separate phases of soil formation (Fig. 8a, b). More in detail, we distinguished a lower GL 7c showing locally preserved planar voids, which were disrupted during a subsequent phase of bioturbation (Fig. 8c). No planar voids were reported in the above GL 7b, which conversely showed more intensive bioturbation (Fig. 8d). Finally, the upper GL 7a appeared compact and disturbed by rare channels that originated from the above GL 6 (Fig. 8e).

Fragmented lithic artifacts, bones, grains of phosphatic sediment, and coprolites are scarce in GL 2 and GL 7 and are nearly absent in the upper part of these deposits (GL 2a and GL 7a). Most of the bone fragments appear coated and/or impregnated with iron and manganese oxides (Fig. 6d). Few faunal materials from GL 2b might have been exposed to heat as shown by the color shifted toward greyish blue in XPL (Fig. 6e) and pale grey in PPL. In GL 2b, chert fragments are smaller than 0.5 mm, whereas at the bottom of GL 7 (GL 7c), we identified a flake measuring 5 cm in length (Fig. 8b). This artifact lies nearly vertical, and it is coated with compound layers of clay and silt (Fig. 9a). The flake is also coated with calcium carbonate, which, in some areas, diffuses into calcite hypocoatings that formed in the surrounding groundmass (Fig. 9b), while, in other areas, shows a sharp border (Fig. 9c).

<u>GL 1 in Section West and GL 6 in Section East</u> The contact separating GL 2, in Section West, and GL 7, in Section East, from the above sediments is sharp, smooth, and wavy, although bioturbated. In Section West, this contact slopes toward outside the Western opening with an angle of ca. 45°, whereas in Section East, it dips toward the Southern entrance with an angle of ca. 30°. GL 2 is covered with unsorted, fine to coarse, triaxial, subangular, fresh limestone gravel embedded in dark grey (7.5 YR 4/1) to very dark grey (7.5 YR 3/1) sandy silt (GL 1 in Fig. 2). Within GL 1, we distinguished an upper GL 1a, almost entirely composed of limestone gravel, and a lower GL 1b, richer in fine fraction. Overall GL 1 appears intensively bioturbated, as shown by high porosity, frequent root fragments, random arrangement of the components, and lack of sorting. In Section East, GL 7 was buried with a 2- to 5-cm-thick laminated deposit (Fig. 8a). Within GL 6, we observed grey (7.5 YR 4/1), well-sorted laminations of fresh loess, alternating with less sorted, very dark grey (7.5 YR 3/1), decalcified layers richer in phosphate and clay (SOM Fig. S2e). The first type of laminations is more frequent in the upper half of this unit (GL 6a), whereas the latter is dominant in the lower half (GL 6b).

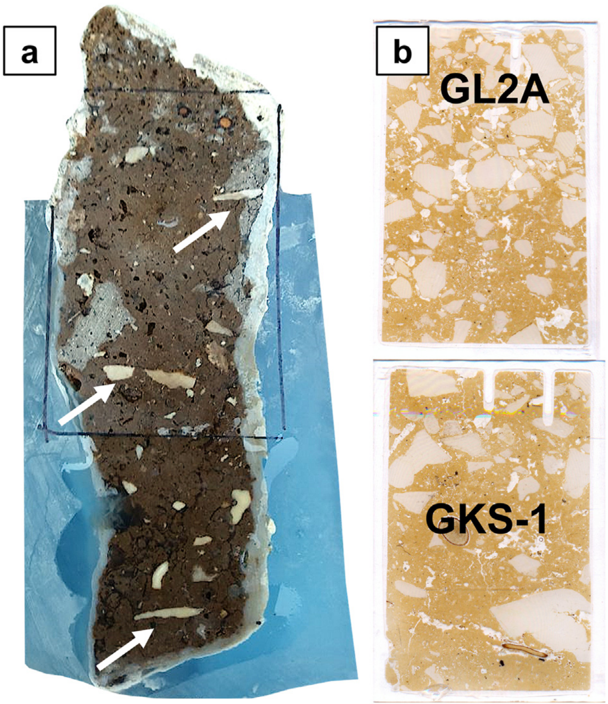

Figure 7. Bergkies from the German Jura. a) micromorphological slab from the loess-rich geological layer (GL) 2B, from Felsenhäusl-Kellerhöhle, showing rare, well-sorted, immature limestone gravel. White arrows indicate potential sedimentary surfaces. This type of limestone gravel is known in Southern Germany as Bergkies (see discussion). The accumulation of this type of deposit began at Felsenhäusl-Kellerhöhle likely after 14.0 ± 0.8 ka. b) thin sections capturing the gradual contact between GKS-1 and GL2A from the entrance to Hohlenstein-Stadel, in the Lone Valley (modified from Barbieri and Miller, 2019b). These sediments appear richer in Bergkies as well as coarser limestone fragments and formed between 16.7 and 13.7 ka cal BP (Hornauer-Jahnke, 2019). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

3.2. Geoarchaeological results from Klausennische

In this section, we summarize our main micromorphological results from Klausennische. Detailed descriptions can be found in SOM Table S4.

GL 4 From a stratigraphic point of view, GL 4 is the lowermost deposit we unearthed at the rock shelter. This layer was encountered above the bedrock in subsquare E 1004/N 1995d, between 30 and 40 cm below the ground surface. GL 4 is loose and is made from yellowish brown to brown (10 YR 5/4 to 7.5 YR 5/4) reworked and decalcified loess, comminute organic matter, reworked clay coatings, iron-manganese nodules, and aggregates made from clay and quartz (Fig. 10). Embedded in this groundmass, we identified common coprolites and phosphatic aggregates (SOM Fig. S4f), limestone gravel, lithic artifacts, bones, teeth, and rare charcoal fragments (the archaeological material is currently under study). The edges of quartz grains and smaller chert fragments are dissolved and replaced in situ by amorphous silica, micritic calcite (SOM Fig. S3f), and rarely clay (SOM Fig. S3c). Most of the bones appear well preserved (Fig. 6g), whereas few of them are calcined (Fig. 6h). Very few bones have been extensively dissolved and partly recrystallized in amorphous apatite (Fig. 6i). Fragments of limestone and speleothem display diffuse, phosphatized rims (Fig. 10f). In the Eastern portion of our micromorphological sample, GL 4 appears better preserved, showing intact beds of gravel separated by microlaminated silty clay (Fig. 10c). Larger, elongated components within these beds, including a potential fragment of lithic artifact (Fig. 10e), are buried in subhorizontal position. The Western side of our sample appears more disturbed, and GL 4 is no longer visible (Fig. 10c). The lateral discontinuity of this layer is in agreement with our field data, which suggests that GL 4 is located at the northern margins of the trench excavated in the early 20th century (Fig. 4).

GL 5 and 6 While our excavation in subsquare E 1004/N 1995 reached the limestone floor at a maximum depth of 40 cm below the ground surface, in subsquare E 1007/N 1992d and b, we dug down to a depth of 70 cm without hitting bedrock. At the bottom of this excavation, we distinguished GL 5. This layer shows a thickness of at least 15 cm (excavation not yet completed) and appears to slope toward the back of the rock shelter with an angle of 15–20°. GL 5 is composed of common (60%) fine to coarse gravel-sized, subrounded, weathered limestone fragments buried in a yellowish red (5 YR 5/8) clayey silt. On top of this layer, we distinguished a separate sediment (GL 6), which fills part of the depression delimited by the upper contact of GL 5. The transition between the two layers is clear. GL 6 is at least 5 cm thick (excavation not yet completed), reddish yellow (7.5 YR 6/8), and is composed of silt with rare (35%) gravel. No archaeological material was found in these deposits. In the future, we plan to continue the excavation of these sediments and study them with luminescence and micromorphological methods.

GL 1 and GL 3 Above the smooth and sharp upper contact of GL 4 in E 1004/N 1995d and GL 6 in E1007/N 1992d, we exposed a sediment (GL 1) made from yellow (10 YR 7/6) to yellowish brown (10 YR 5/4) silty clay/clayey silt, with rare sand and rare angular limestone gravel. This deposit shows a maximum thickness of 25 cm and yields a few undiagnostic Upper Paleolithic lithic tools and rare faunal remains. We exposed GL 1 also in squares E 1001/N 1994d and b, E 1002/N 1995a, E 1007/N 1993d. The excavation of the lowermost 10 cm of GL 1 in square E 1004/N 1995d unearthed a Keilmesser knife. As the sediment surrounding this find appeared slightly browner and somewhat richer in silt than the rest of GL 1, the excavator distinguished this as a separate GL 3 (Fig. 4). Subsequent on-site geoarchaeological assessments, however, revealed that the observed lithological properties of GL 3 are within the variability of the above GL 1. Therefore, in this article, we consider GL 3 and GL 1 exposed in E 1004/N 1995d as part of the same geological layer. Under the microscope, GL 1 in E 1004/N 1995d appears intensively bioturbated and exhibits aggregates composed of granostriated clay, bones, phosphates, and chert fragments, which likely originated from the lower GL 4 or from similar sediments (Fig. 10b). On the other hand, GL 1 in E1007/N 1992d and b corresponds to at least three graded beds of nonphosphatic, crystallitic loess (GL 1a, b, c; Fig. 8f, g), which show horizontal, moderately separated, and partly accommodating planar voids, resulting from the formation of ice lenses (Fig. 8h–j). Although they are generally well preserved, these voids are partly disrupted by the subsequent formation of channels and chambers. This process was more intensive in GL 1b, as shown by the higher frequency of biogenic voids and the localized aggregation of the groundmass in granules (Fig. 8i). GL 1 in E1007/N 1992d and b shows a few components that possibly eroded from a separate sedimentary source, such as angular to subangular sand grains of bone, phosphate, chert, and speleothem, which are coated with limpid to dusty clay and, in few cases, are impregnated with iron-manganese oxides (Fig. 8h–j).

GL 2 and GL 0 The upper contact of GL 1 is clear to sharp, wavy and it is covered with a 10- to 15-cm-thick layer rich (80%) in fine and coarse, triaxial to oblate, angular, and fresh limestone gravel, which rests horizontal within a clayey silt with rare calcite sand (GL 2). In some excavation areas, within GL 2, we distinguished a lower, brown (10 YR 4/3) sublayer (GL 2b) and an upper, dark brown to brown (7.5 YR 3/2 to 4/2) deposit (GL 2a). Toward the center of our

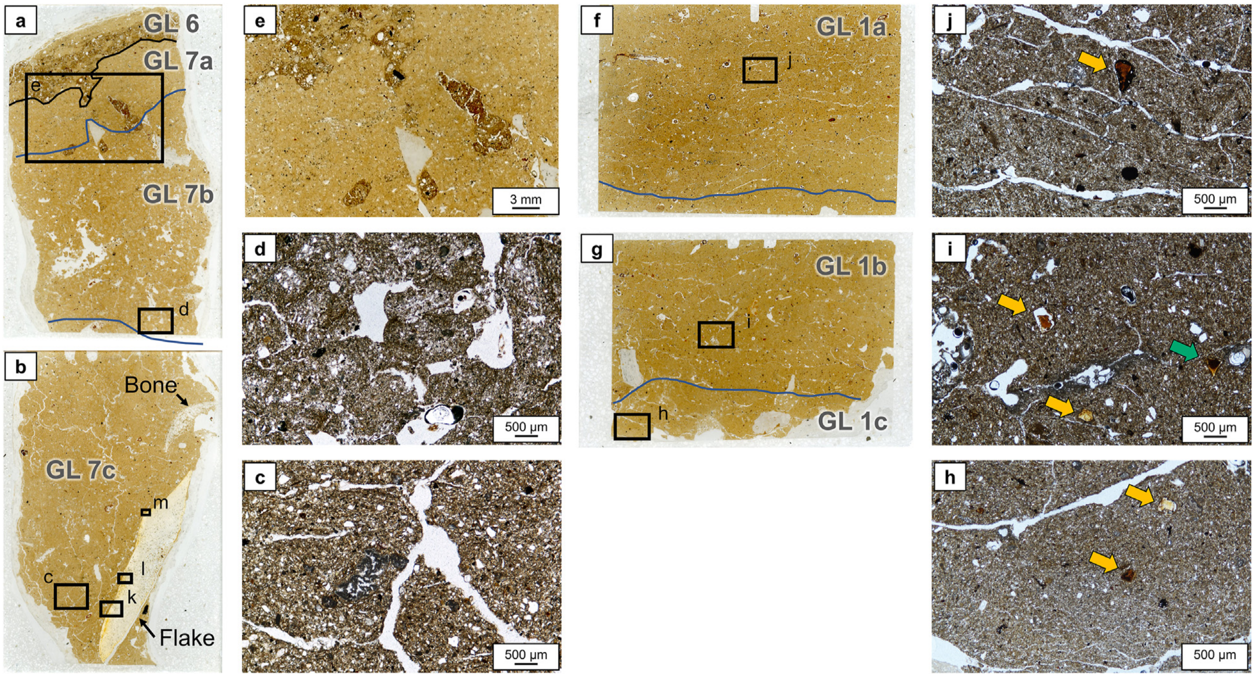

Figure 8. Loess deposition, freezing-thawing, and bioturbation at Felsenhäusl-Kellerhöhle and Klausennische. a, b) Thin section scans of geological layer (GL) 7 and GL 6, Felsenhäusl-Kellerhöhle. c) Parallel, horizontal, planar voids partly disrupted by subsequent formation of channels from GL 7c (photomicrograph taken in plane polarized light [PPL]). d) Higher frequency of voids and granular aggregates in GL 7b, showing more intensive bioturbation (PPL). e) Channels translocating sediment from GL 6b into the underlying, massive GL 7a and GL 7b (detail from thin section scan). f, g) Thin section scans from GL 1 in square E1007/N 1993, Klausennische. h) Well sorted loess exhibiting planar voids, from GL 1c (PPL). i) Coarser reworked loess with more frequent and larger biogenic voids, from GL 1b (PPL). j) Frequent planar, parallel voids from GL 1a (PPL). In panels h–j, grains of phosphatized loess and bone are depicted with orange and green arrows, respectively. Labels k–m in panel b) indicate the location of the panels a–c) depicted in Figure 9. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

excavation grid, GL 2 appears to rest directly on top of the bedrock, suggesting that this layer might correspond to the backfill of previous excavations. The modern and man-made nature of this layer is also suggested by the occurrence of oblate limestone fragments locally known as Solnhofener Plattenkalk, which consist of limestone slabs traditionally used as a building material. Above GL 2, we distinguished GL 0, which is loose, rich in charred vegetal remains, plastic, and metal fragments. It shows black color (Gley 1 2.5/N) with greenish black (Gley 1 2.5/1) and white (Gley 1 8/N) speckles.

3.3. Site formation processes at Felsenhäusl-Kellerhöhle and Klausennische

Felsenhäusl-Kellerhöhle GL 4 is the lowermost sediment we investigated from Section West in Felsenhäusl-Kellerhöhle. This sediment is rich in grains of phosphatized loess and fragments of carnivore coprolites (SOM Fig. S4a). These components are not buried in situ, as indicated by the groundmass of GL 4, which is made from nonphosphatic reworked loess. Similarly, bone fragments from GL 4 are not in primary deposition, as we documented fresh faunal remains lying next to burnt and dissolved bones (Fig. 6a–c). In sum, our micromorphological results show that GL 4 originated from the redeposition of separate geological deposits and archaeological remains. Previous lithic analysis revealed that the lowermost spit excavated from Felsenhäusl-Kellerhöhle yielded mixed Middle and Upper Paleolithic materials (Fig. 2; Hattermann et al., 2019). This and the other spits, however, were removed from this site without respecting its stratigraphy. On the contrary, each of them encompasses separate and distinct deposits (Fig. 2). Therefore, it remains difficult to prove whether the mixed archaeological assemblage known from the lowermost and the above spits reflects poor excavation methods or the formation history of the cave infilling.

In GL 4, the groundmass is organized in discontinuous, horizontal, wavy, graded laminations (Fig. 5b), while coarser fragments show weak imbrication (Fig. 5a) and exhibit coatings of sand, silt, and clay (Fig. 5c, d). Similar structures are commonly reported from sediments exposed to repetitive freezing in periglacial environments (Romans et al., 1966, 1980; Fedoroff et al., 1981; Coutard et al., 1988; Van Vliet-Lanoë, 1988). In GL 4, we observed in situ infillings and coatings of clay, which appear more numerous in the lower portion of our sample. Good preservation of these pedofeatures shows that clay illuviation occurred when gelifluction was less intensive or no longer active, possibly due to a shift toward drier winters (Van Vliet-Lanoë and Fox, 2018).

In Section West, GL 4 is buried below GL 3, which we did not sample for micromorphology because of its coarse grain size. Further analyses are necessary to reconstruct the processes that led to the formation of this deposit. We have not observed sediments similar to GL 4 and GL 3 in Section East. This can be explained with two alternative hypotheses. (1) GL 4 and GL 3 accumulated only in the immediate proximity of the cave entrance(s) and did not extend to Section East, due to the uneven cave floor. (2) Alternatively, GL 4 and GL 3 were removed from Section East (and other parts of the cave) either by human action and/or by geogenic processes. Considering that the cave floor deepens toward Section West, GL 4 might have originated from the Westward movement of sediments within the cave. Part of GL 4 might have also moved out from the cave through an opening located at the bottom of Section West, which we have not yet identified. GL 3 rests mostly above the higher areas of the cave floor, therefore geogenic erosional processes might have moved part of GL 3 out of the cave also through

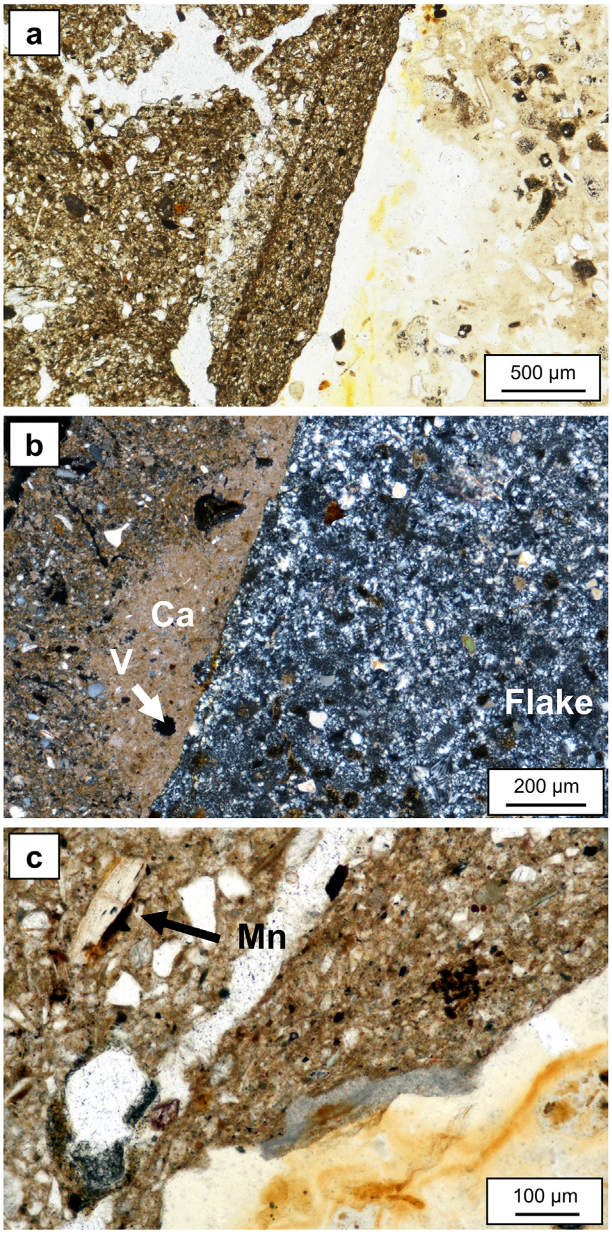

Figure 9. Details from the partly reworked flake in GL 7c. Location of photomicrograph is depicted in Figure 6b. a) Silt and clay coating the lithic artifact in plane polarized light (PPL). b) Calcite hypocoatings (Ca) formed around channel void (V) in the proximity of the flake (crossed polarized light [XPL]). c) Photomicrographs capturing a separate sharp, calcite coating formed along the flake edge (PPL). In the surrounding sediment, a bone fragment coated with manganese oxides (Mn). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

the Eastern entrance. The hypothesis of an erosional phase before the accumulation of loess-rich deposits at Felsenhäusl-Kellerhöhle seems corroborated by the fact that in Section West, GL 2 rests in nonconformity with the lower GL 3, and in Section East, GL 7 covers directly the bedrock (Fig. 2).

Our micromorphological data from GL 2 and GL 7 indicate that these deposits were accumulated by similar, alternating processes. In the lower part of GL 7 (GL 7c), we observed locally preserved platy microstructure (Fig. 8c), which resulted from ground freezing (Van Vliet-Lanoë and Fox, 2018). This microstructure was nearly entirely disrupted by subsequent bioturbation, which was more intensive after the deposition of GL 7b (Fig. 8d). The upper GL 7a appears compact and was bioturbated only after its burial, as shown by root channels that moved sediment from the above GL 6b (Fig. 8e). The alternation of loess accumulation and sedimentary pauses is documented also in GL 2b, where we observed intact depositional surfaces delimited by rare immature, sorted (<2 cm long) limestone fragments (Fig. 7a). This type of gravel is known in Southern German geomorphological and archaeological literature as Bergkies and is commonly interpreted as resulting from the frost breakage of exposed limestone bedrock (Wolff, 1962; Riek et al., 1973; Campen, 1990; Barbieri et al., 2018; Barbieri, 2019). Our micromorphological data show that GL 2 and GL 7 contain little potential archaeological material, such as heated bones and lithic artifacts. Beds within these deposits, like GL 7a, are nearly entirely free from these components. This observation confirms results from previous lithic studies, which show an upward decrease in the frequency of lithic tools through the sequence of Felsenhäusl-Kellerhöhle (Hattermann et al., 2019). In GL 2 and GL 7, lithic and bone fragments show mixed diagenesis (as documented for GL 4), suggesting that most of these materials did not preserve in situ but were reworked from multiple sediment sources. In GL 7c, we documented a 5-cm-long chert flake, which was moved in vertical position and coated with silt by frost jacking and gelifluction (Fig. 8b; Beskow, 1947; Kaplar, 1965; Pissart, 1969; Van Vliet-Lanoë and Fox, 2018). Unlike other bone and lithic fragments from GL 7c that show clay coatings stained with manganese oxides (Fig. 9c), this flake is coated with calcium carbonate and silt from the groundmass (Fig. 9a, b). This observation suggests that the primary depositional context of this artifact is probably GL 7c, or a similar sediment. Furthermore, this flake is much bigger (medium gravel) than the mean grain size of the sediment in which it is buried (clayey silt), suggesting that it was probably abandoned by humans not far from Section East.

The upper contact of GL 2 and GL 7 appears sharp, indicating that it has been shaped by erosional processes, and it slopes toward outside both cave openings. Such erosion was probably triggered by geomorphological processes occurring downslope from the site. Alternatively, it is possible that humans removed part of the sediments that filled the cave to use it more comfortably. Above this disconformity, we reported GL 1b in Section West and GL 6 in Section East, which are richer in rounded quartz sand exhibiting intensive weathering (SOM Fig. S3e). Such change in sedimentary source and diagenesis might be related with the more intensive erosion of fluvial deposits (similar to the ‘Bohnerz’ formation; Borger and Widdowson, 2001; Ufrecht, 2008), which accumulated on top of Felsenhäusl-Kellerhöhle before the Pleistocene. Sedimentary structures are visible in GL 6, as shown by graded laminations of fresh loess alternating with decalcified, phosphatized, clay-rich layers (SOM Fig. S4e). Based on these characteristics, we argue that run-offs accumulated GL 6 during cold and dry climate alternating with warmer and wetter intervals. Although GL 6 is not significantly bioturbated, GL1b appears intensively disturbed by modern plants that grew outside the entrance, on top of Section West. Apart from quartz sand, GL 1b exhibits also medium gravel-sized fragments of fresh speleothems and limestone fragments, which rarely appear phosphatized. The higher frequency of these components shows that the breakage of the cave walls and ceiling played an important role in the accumulation of this deposit, probably due to its proximity to the Western entrance. Although absent in GL 1b, bone and charcoal fragments occur in GL 6. These show one predominant type of diagenesis, iron-manganese oxidation, revealing that the archaeological materials buried in GL 6 are probably less mixed than in the lower deposits. A diminished redeposition of archaeological material is probably related with the fact that, during the accumulation of GL 6, older archaeological

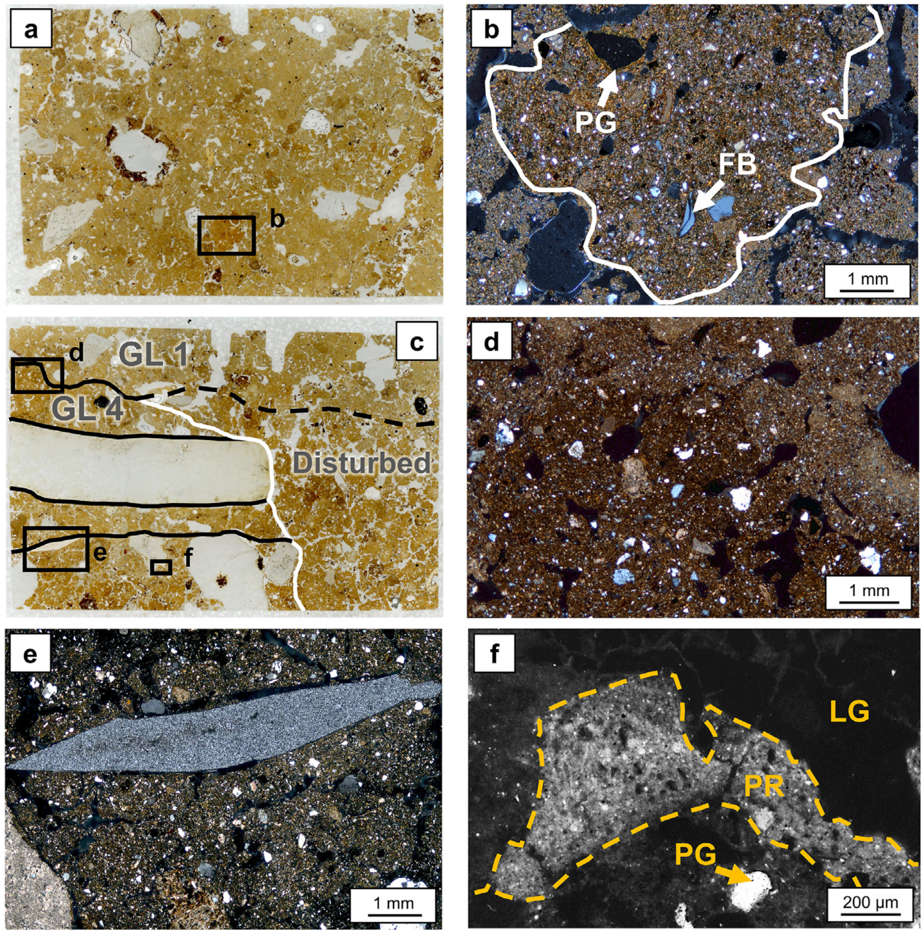

Figure 10. Transition from the in situ geological layer (GL) 4 to the reworked GL 1 in subsquare E 1004/N 1995c. a) Thin section scan from GL 1. b) White line delimits an aggregate rich in clay, phosphatic grains (PG), and fresh bone (FB) fragments (crossed polarized light [XPL]). c) Thin section scan from the passage between GL 4 and GL 1. The right portion of the slide (West) appears disturbed, while the left (East) side of the sample exhibits graded bedding. d) Sharp contact between the upper GL 1, richer in silt and calcite, and the underlying GL 4, decalcified and richer in clay (XPL). e) Flake lying flat (probably in situ) in the upper part of the lowermost gravel bed from GL 4 (XPL). f) Border of a limestone gravel (LG) dissolved and replaced with phosphate (PR) lying next to a phosphatic grain (PG; reflected blue light). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

Table 1
Dosimetry data, equivalent dose (De) values, and luminescence age estimates obtained using the post-infrared-infrared (pIRIR225) approach on polymineral fine grains. The table also lists the single alpha, beta, and gamma dose rate contributions. For both samples, a water content of 20 ± 10% was assumed. The high error (10%) was chosen with respect to uncertainties with the water content that fluctuated over relevant time scales.

Field code	Sample ID (L-Eva)	U (ppm)	Th (ppm)	K (%)	Alpha DR	Beta DR	Gamma DR	Total DR (mGy/a)	De (Gy) pIRIR225	pIRIR225 age (ka)
Klau-Ni-1	2055	3.4 ± 0.4	10.9 ± 0.7	1.7 ± 0.2	0.91 ± 0.13	1.68 ± 0.16	1.02 ± 0.11	3.68 ± 0.24	59.3 ± 1.4	16.1 ± 1.1
Fe-Häusl-1	2058	3.4 ± 0.4	11.7 ± 0.8	1.8 ± 0.1	0.94 ± 0.13	1.77 ± 0.14	1.08 ± 0.11	3.85 ± 0.22	54.0 ± 0.3	14.0 ± 0.8

Abbreviation: DR = dose rate.

deposits within Felsenhäusl-Kellerhöhle and in its close surroundings were deeply buried or extensively removed.

The top of Section East is truncated, with a 40 cm gap between GL 6 and the bottom of speleothem formation that used to cap this part of the cave sequence (Fig. 2). It is unclear whether these sediments were removed from this part of the cave during the modern excavation or in historical times, when the cave, like many caves and rock shelters in the region (e.g., Sesselfelsgrotte, Freund, 1998), most probably served as a storage space. On the other hand, the sequence in Section West appears intact and terminates with GL 1a. The latter, together with the upper part of GL 1b, most likely corresponds to the uppermost spit excavated at the site (Fig. 2), which yielded potential Magdalenian tools (Hattermann et al., 2019). We did not sample GL 1a because of its high amounts of fresh limestone gravel, including Bergkies. Its lithology, however, clearly shows that the Magdalenian materials accumulated inside Felsenhäusl-Kellerhöhle during a period characterized by more intensive breakage of the cave walls and ceiling, probably under increased frequency of freezing and thawing cycles (Riek and Heller, 1957; Riek et al., 1973; Campen, 1990; Freund, 1998; Barbieri et al., 2018; Barbieri, 2019).

Klausennische GL 4 is the lowermost sediment we unearthed in subsquare E 1004/N 1995d. This layer rests above the limestone bedrock and yields faunal remains and potential Middle Paleolithic artifacts. These findings match with the two separate Neanderthal occupations that were previously uncovered from sediments stratigraphically comparable with GL 4 (Birkner, 1936; Bosinski, 1967). Study of the archaeological materials and absolute dating are needed to confirm the attribution of GL 4 and its assemblage to the Middle Paleolithic.

Our micromorphological results revealed that GL 4 is composed of gravel beds and microlaminated clay layers, which originated from alternating colluvium and surface run-off (Fig. 10c). The colluvial beds appear to be richer in archaeological materials. Among these, faunal remains range from well-preserved to dissolved and heated (Fig. 6g–i), indicating that they were reworked/eroded from various sedimentary sources located within Klausennische and possibly from the above cave of Mittlere Klause (Fig. 3a). The accumulation of GL 4, however, was not a continuous process but alternated with sedimentary breaks, during which stable surfaces might have been exploited by Neanderthals. This is suggested, for instance, by a subhorizontal lithic artifact capping the lowermost gravel bed (Fig. 10e). After deposition, GL 4 was exposed to high moisture, high temperatures, and fluctuating pH conditions, as shown by the replacement of calcite and quartz with phosphate (Fig. 10f) and calcite (SOM Fig. S3f), respectively. Carnivore coprolites (SOM Fig. S4d) indicate that the phosphatization process was probably triggered by an animal use of the shelter, similar, although less intensive, to what was observed in Middle Paleolithic deposits from the Swabian Jura (Schiegl et al., 2003; Miller, 2015; Barbieri and Miller, 2019b). GL 4 is better preserved in the Eastern part of our sample (Fig. 10c). The more intensive disturbance of GL 4 in the Western area of subsquare E 1004/N 1995d is likely the result of previous works at Klausennische, which removed a considerable portion of the Pleistocene deposits and refilled the site with the excavation back dirt (GL 2 and GL 0; Fig. 4; Birkner, 1936; Bosinski, 1967).

In subsquare E 1004/N 1995d, GL 4 is truncated and covered with the nonphosphatic and loess-rich GL 1. In the field, this layer appeared to extend across multiple excavation squares. Our micromorphological study, however, revealed that this unit may not be as laterally continuous as expected. GL 1 in E 1004/N 1995d lacks sedimentary structures, appears extensively bioturbated (Fig. 10a), and covers GL 4, which was partly disturbed during previous works at the site (Fig. 10c). Based on these observations, we interpret GL 1 from E 1004/N 1995d either as a Pleistocene deposit bioturbated with the above modern sediments (GL 2 and GL 0) or as back dirt from previous excavations. This latter view seems supported by the occurrence of a Middle Paleolithic backed bifacial knife (Keilmesser) in GL 1 in E 1004/N 1995d. Previous excavations at Klausennische reported similar Keilmesser knifes (Obermaier and Wernert, 1914; Bosinski, 1967), it is possible that the one we recovered was not recognized during the previous excavation and was redeposited during backfilling. It remains to be further investigated whether the sharp contact separating GL 1 from GL 4 (Fig. 10c, d) is the result of geogenic erosional processes or modern anthropogenic disturbance.

Contrary to GL 1 from E 1004/N 1995d, GL 1 unearthed in subsquares E 1007/N 1992b and d (from here on GL1a–c) shows sedimentary- and microstructures (Fig. 8f–j) as well as dating (16.1 ± 1 ka) compatible with a Late Pleistocene deposit. This sediment is bedded and shows grading indicative of water deposition (Bertran and Texier, 1999). Based on this observation, we hypothesize that water discharged during snowmelt moved windblown loess from above Klausenhöhle toward Klausennische, where it accumulated as GL1a–c. A similar process has been described for loess sequences deposited in the Lone and Ach valleys of the Swabian Jura (Barbieri et al., 2018, 2021; Barbieri, 2019). After sedimentation, GL1a–c was reworked by freezing and thawing processes, which opened horizontal, parallel, planar voids, and rolled and jacked upward coarse sand-sized bone and chert fragments (e.g., Fig. 8j; Beskow, 1947; Kaplar, 1965; Pissart, 1969; Van Vliet-Lanoë and Fox, 2018). The spacing and size of planar voids is smaller in the upper bed of GL1a–c, GL1a (Fig. 8j), and coarser in the lower bed, GL1c (Fig. 8h), showing that the repetitive formation of ice lenses occurred in at least two distinct 'generations' of freezing and thawing (Van Vliet Lanoë, 1976; Mestdagh, 2005; Van Vliet-Lanoë and Fox, 2018). These two generations were separated by a slight change in environmental conditions, which allowed for a more intensive bioturbation in GL 1b (Fig. 8i).

Only one flint artifact was unearthed from the excavation of GL 1a–c. Our micromorphological study also detected sand-sized bone and chert fragments. Although it is possible that some of these materials are buried in situ, we cannot exclude that they were reworked from upslope areas within Klausennische or from the above Mittlere Klause (Fig. 3).

3.4. Comparing geoarchaeological and luminescence dating results

We performed pIRIR225 measurements on fine silt fraction (4–11 μm; polyminerals; 9 aliquots per sample) dating GL 7c at Felsenhäusl-Kellerhöhle to 14.0 ± 0.8 ka and GL 1b at Klausennische to 16.1 ± 1.1 ka (Table 1). The choice of performing the pIRIR225 measurements on this grain size was based on the results of our micromorphological study, which showed that the fine silt of GL 7c at Felsenhäusl-Kellerhöhle and GL 1b at Klausennische accumulated through the alternation of wind-blown deposition during winter and reworking by run-off and gelifluction during snowmelt. Hence, the aeolian transport is regarded to have bleached down the luminescence signal of the 4–11 μm fraction sufficiently. Considering the likely short time interval (possibly even seasonal) between primary deposition (last sunlight exposure) and secondary (re)deposition inside the cave, we expect that the reworking process had no measurable impact on the luminescence age, meaning that the last sunlight exposure is almost fully analogue with the final burial of the sediment. Dose residuals, if present, should have a minor effect on our pIRIR225 age estimates. During secondary deposition, rare sand-sized components (e.g., bone, chert) were also redeposited in GL 7c at Felsenhäusl-Kellerhöhle and GL 1b at Klausennische. These components, which might have been reworked from older sediments, do not impact our luminescence dating, as this was performed on the finer silt fraction.

Post depositional mixing processes, caused for instance by bioturbation or cryoturbation, might bias the equivalent dose we calculated for our luminescence samples. In our thin sections, we did not find any evidence that the formation of ice lenses in GL 7c and GL 1b caused the movement of silt from overlying or underlying deposits. Despite being bioturbated, GL 1b at Klausennische can be regarded as a rather intact deposit, as it is sandwiched between two layers (GL 1a and GL 1c) which show limited evidence of bioturbation (Fig. 8i–m). On the other hand, we cannot exclude that the intensive bioturbation we observed throughout GL 7c and the above GL 7b at Felsenhäusl-Kellerhöhle (Fig. 8a–d) might have caused the redistribution of silt across these deposits. Therefore, additional dating is necessary to investigate the possibility of an age underestimation of GL 7c.

Although we were not able to perform in situ gamma dose rate measurements (Table 1), the hypothesis that our luminescence results are biased by the different gamma dose rate of under- and/or overlying sediments is improbable at Klausennische, where GL 1b is deposited between sediments exhibiting similar lithology and micromorphology. On the other hand, the luminescence sample from GL 7c at Felsenhäusl-Kellerhöhle was collected only 15 cm above the limestone cave floor and thus might have been affected by the different gamma dose rate of the bedrock. Assuming low radioactivity for the limestone, we expect that the true gamma dose rate affecting sample Fe-Häusel-1 is slightly lower than reported in Table 1. Therefore, the age estimate of sample Fe-Häusel-1 might be discussed as slightly underestimated. As no scientifically evidenced dosimetry values are known from the limestone, it is not possible to precisely quantify this underestimation without in situ gamma dose rate measurements. Further work to minimize such uncertainty is required. Nevertheless, we expect that the influence of gamma dose rate heterogeneity should not significantly influence the total dose rate and the final luminescence age estimate of this deposit, also considering that a potential age underestimation might be masked by dose residuals of the pIR225 signal (additional information and discussion, including dosimetry, can be found in SOM S2).

In conclusion, the luminescence dates presented in this article provide a first and yet reliable chronological framework (for a more technical discussion, see SOM S2). Additional luminescence ages, preferably in combination with radiocarbon dates, are required especially at Felsenhäusl-Kellerhöhle, to obtain a higher chronological resolution.

4. Discussion

4.1. Environments and foragers in the Franconian and Swabian Jura at the end of the Last Glacial Maximum

Recent studies revealed that environments and geomorphological processes were probably out of sync across the Alpine region and the Swabian Jura during and after the LGM (Monegato et al., 2017; Barbieri et al., 2021; Gribenski et al., 2021). These finds open the possibility that Magdalenian foragers settled in the Franconia 2 ka later than in the Swabian Jura due to environmental differences across the two regions. In this section, we use data published in this article and in other recent studies to explore this hypothesis.

4.2. Paleoenvironments and Magdalenian foragers in the Lone Valley, Swabian Jura

The rock shelter of Langmahdhalde, in the Lone Valley, is the only site from the Swabian Jura that shows a nearly continuous stratigraphy dating between 22 and 14 ka cal BP (Conard et al., 2018; Wong et al., 2020a; Publication of additional dating is underway, N. Conard personal communication 2021). This sequence shows a passage from sterile loess (GH7 and below) to Magdalenian Bergkies (GH3–6; A. Varis personal communication 2021), which probably reflects a transition to a wetter climate with more frequent freezing and thawing cycles (Riek and Heller, 1957; Riek et al., 1973; Campen, 1990; Freund, 1998; Barbieri et al., 2018; Barbieri, 2019). This transition occurred before 16 ka cal BP (Conard et al., 2018 and personal communication 2021). Unlike Langmahdhalde, most caves and rock shelters from the Lone Valley were intensively eroded between 35 and 17 ka cal BP, while a similar erosional phase occurred in the neighboring Ach Valley between 30 and 16 ka cal BP (Barbieri et al., 2021). The removal of sediments and materials from the sites of the Swabian Jura was related with a regional phase of hillside instability, resulting from the joint action of river valley incisions, de-vegetation, and intensive snowmelt (Barbieri et al., 2018, 2021). Disconformities in caves of both valleys were covered with sediments rich in Bergkies and Magdalenian materials dating as early as 17–16 ka cal BP (Barbieri et al., 2018, 2021; Barbieri, 2019; Barbieri and Miller, 2019a). This stratigraphic position makes it difficult to establish whether this region was indeed de-populated (Jochim et al., 1999; Terberger and Street, 2002; Terberger, 2003; Küßner and Terberger, 2006) or continuously visited by hunter-gatherers before the permanent settlement of Magdalenian foragers (Maier, 2015; Maier et al., 2020; Barbieri et al., 2021).

Numerous studies further enlighten that between 17 and 15 ka cal BP, climate in the Lone Valley was cool. Micromorphological data from this period are available only from one Magdalenian deposit that accumulated at the entrance to Hohlenstein-Stadel around 16.7 ka cal BP (GKS-1 in Fig. 7; Barbieri and Miller, 2019a; Hornauer-Jahnke, 2019). This deposit does not show microfeatures indicative of repetitive ground freezing (Barbieri and Miller, 2019a). This observation matches the lack of similar microfeatures in deposits filling the Ach and Lone valleys, which have been tentatively dated between the LGM and the Late Glacial (Barbieri et al., 2018; Barbieri, 2019). Microfaunal analysis from GKS-1 and GL 2A revealed a mixture of tundra and forest species (Ziegler, 2019). Similar signal was also detected by a separate microfaunal study, conducted on the coeval GH3-6 sediments from Langmahdhalde (Wong et al., 2020b). In addition, isotopic analysis performed on materials from the same GH3–6 deposits indicated a cold climate, but with higher rainfall and shorter winters in comparison with modern tundra environments (Wong et al., 2020a).

In sum, these studies revealed that Magdalenian foragers regularly exploited the Lone Valley between 17 and 14 ka cal BP, when climate in this region was cool, melting periods were frequent and longer lasting, and the landscape was covered by grasses and patches of forest (Ziegler, 2019; Barbieri and Miller, 2019a; Wong et al., 2020a, 2020b). These observations agree with previous studies (Birks and Willis, 2008; Tóth et al., 2017; Grimm, 2019), contradicting the hypothesis proposed by (Taller 2014; Taller et al., 2014) that Magdalenian foragers spread across an arid and deforested landscape. This conclusion is also in line with recent isotopic and radiocarbon data from Switzerland, which showed that the arrival of Magdalenian foragers followed cool oscillations (Reade et al., 2020a, 2020b).

4.3. Paleoenvironments and foragers in the Altmühl Valley, Franconian Jura

An archaeological and environmental shift similar to the one observed at Langmahdhalde and Hohlenstein-Stadel might have occurred in the Altmühl Valley, but with a different chronology. At Sesselfelsgrotte, the sterile and loess-rich layer D, dating to 16.2 ± 1.9 and 16.3 ± 1.5 ka, is buried below the Bergkies and Magdalenian materials of layer C2, ranging between 15.5 and 14.5 ka cal BP (Fig. 11; SOM Table S2; Housley et al., 1997; Freund, 1998; Richter et al., 2000; Böhner, 2008). Comparable to layer D of Sesselfelsgrotte, GL 1a–c at Klausennische exhibits high loess content, only one lithic artifact, evidence of ground freezing, limited bioturbation, and a luminescence age of 16.1 ± 1.1 ka (Table 1; Fig. 11). Geochronology and lithology of these two deposits as well as micromorphological observations from layer GL 1a–c of Klausennische are compatible with the Gschnitz Stadial, a dry oscillation observed in the Central and Eastern Alps (ca. 17–15 ka), which has been correlated with the Heinrich Event 1 in the North Atlantic (Wright, 2001; Ivy-Ochs et al., 2006; Iriondo and Kröhling, 2007). During this stadial, glaciers advanced in the Inn Valley (Ivy-Ochs et al., 2008) and in the Kleiner Arbersee basin, in the Bavarian Forest (KA in Fig. 1; Reuther et al., 2011). The front of these glaciers was located 90–100 km to the South and East from the Altmühl Valley. Despite its short duration, glacier-climate models revealed that this stadial was particularly extreme, with moisture advection originating from the Mediterranean Sea and annual precipitation decreasing by 70% along the Northern side of the Alps (Ivy-Ochs et al., 2008). The lack of comparable harsh conditions between 17 and 15 ka cal BP in the Lone (and possibly Ach) Valley is mirrored by the missing evidence of the Gschnitz Stadial in the Western Alps (Ivy-Ochs et al., 2008). In addition, there is no evidence that the Feldberg glacier in the Black Forest (FB in

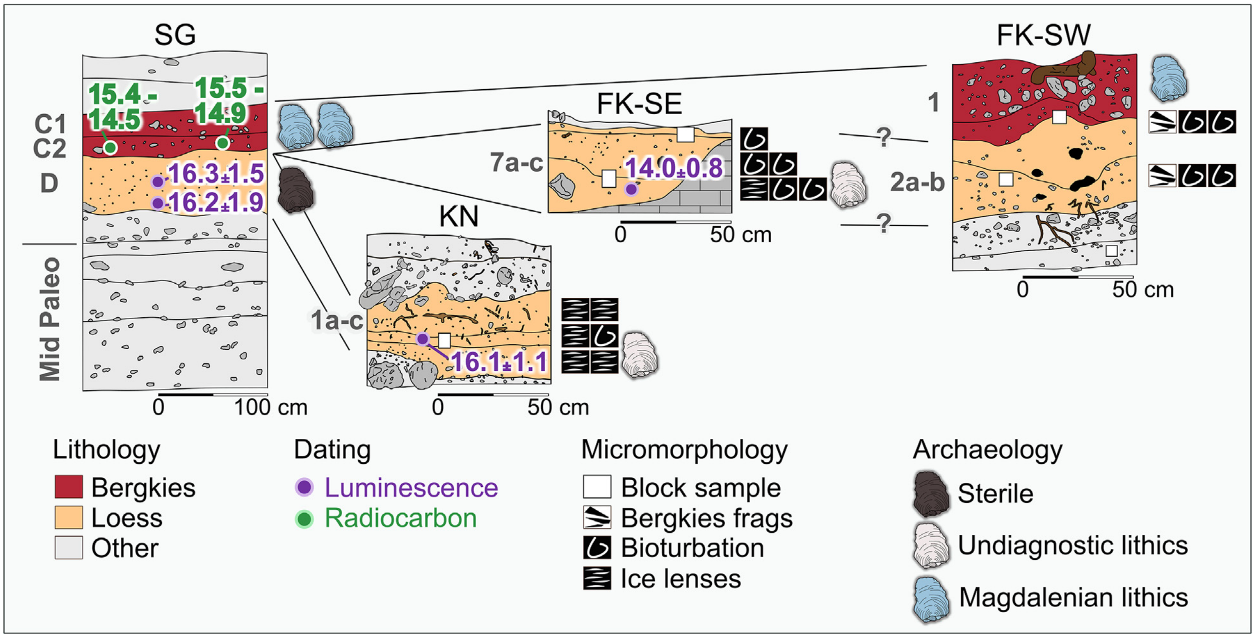

Figure 11. Stratigraphic correlation across Sesselfelsgrotte (SG), Klausennische (KN), and Section East and Section West from Felsenhäusl-Kellerhöhle (FK-SE; FK-SW). The image depicts simplified stratigraphic logs from these sites with key lithological, geochronological, micromorphological, and archaeological data, which are discussed in the main text of the article (the stratigraphic log from Sesselfelsgrotte is modified from Freund, 1984). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

Fig. 1) reached a new maximum during this period (Hofmann et al., 2020).

A modified reindeer antler fragment dating between 16.2 and 15.4 ka cal BP from Mittlere Klause (Housley et al., 1997; SOM Table S2) and the one lithic artifact from GL 1a–c from Klausennische are the only evidence of forager presence in the Altmühl Valley in the period 17–15 ka.

GL 7c in Section East of Felsenhäusl-Kellerhöhle shows high loess content, evidence of ground freezing disrupted by subsequent intensive bioturbation, a partly reworked flake, and a luminescence age of 14.0 ± 0.8 ka (Table 1; Figs. 8b, c and 11). This deposit probably correlates with GL 2 in Section West of the same cave, which shows comparable stratigraphic position, similar lithology, intensive bioturbation, rare Bergkies beds, and very rare chips of lithic artifacts (Figs. 7 and 11). These sediments might indicate short-lived forager stays at this site during a slight climatic improvement at the end of the 17–15 ka stadial (Fig. 11). Further dating, however, remains necessary to confirm the chronology of these deposits.

After the deposition of GL 2, Bergkies sedimentation at Felsenhäusl-Kellerhöhle became predominant in GL 1 (Figs. 2 and 11). This layer probably corresponds to the uppermost spit excavated from this site, which yielded materials typo-/technologically comparable with the Magdalenian assemblage from layers C1 and C2 of Sesselfelsgrotte, which accumulated starting 15.5–14.5 ka cal BP (Housley et al., 1997; Freund, 1998; Terberger, 2008; Hattermann et al., 2019; SOM Table S2). GL 2 from Felsenhäusl-Kellerhöhle and C1–C2 from Sesselfelsgrotte also share a similar lithology, being rich in Bergkies. As discussed for similar sediments from the Lone Valley (see section 4.2), this sediment type reflects a shift toward a slightly wetter climate and more frequent freezing and thawing cycles (Riek and Heller, 1957; Riek et al., 1973; Campen, 1990; Freund, 1998; Barbieri et al., 2018; Barbieri, 2019). From Klausennische, we did not report similar sediments, probably because they were removed during previous works at the site.

In sum, between 17 and 15 ka, foragers ephemerally visited the Altmühl Valley, when the climate was likely cold and dry. Hunter-gatherer occupations peaked in this region between 15 and 14 ka cal BP, as documented by the rich assemblages of Obere Klause, Sesselfelsgrotte, and possibly the small assemblage of Felsenhäusl-Kellerhöhle (Kaulich et al., 1978; Kaulich, 1994; Housley et al., 1997; Kind, 2003; Steguweit, 2011; Hattermann et al., 2019). This phase of intensive occupation possibly coincided with a shift toward cooler and wetter climate characterized by more frequent melting periods, similar to the environmental conditions that dominated the entire Magdalenian occupation of the Lone (and probably Ach) Valley between 17 and 14 ka cal BP. At present, we regard this reconstruction as a working hypothesis which needs to be confirmed with further research, particularly with a larger dating program of caves and rock shelters of the Altmühl Valley.

The hypothesis of a later eastward expansion of improving environments across the German Jura between the LGM and the Late Glacial seems more than plausible when comparing regional paleoenvironmental proxies. Lake records located only 20 km (Bergsee) and 40 km (Moossee) south from the Feldberg glacier (in the Black Forest) indicate that starting 16 ka cal BP, the landscape was colonized by grass, shrub, and rarer dwarf tree species (Duprat-Oualid et al., 2017; Rey et al., 2020). In addition, a rapid deglaciation commenced in the neighboring Swiss plateau as early as 17.4 ka cal BP (Ivy-Ochs et al., 2004; Rasmussen et al., 2014), making quickly available a range of habitats and landscapes for humans and animals to exploit (Drucker et al., 2012; Reade et al., 2020b). On the other hand, the deglaciation of South-Eastern Germany probably occurred with a couple of millennia of delay, as testified by the disappearance of ice and the spreading of tree cover in the Arbersee area (in the Bavarian Forest) only around 14.6 ka cal BP (Raab and Völkel, 2003).

5. Conclusions

Are sites poorer in finds from the Franconian Jura of any use to advance our knowledge on the Magdalenian recolonization of Central Europe? Our work shows that, despite repeated modern excavations and destructions, both Klausennische and Felsenhäusl-

Kellerhöhle hold intact Pleistocene deposits. The frequent occurrence of cave sediments with low amounts of archaeological materials at these and other sites of the Altmühl Valley does not diminish the overall value of the Upper Paleolithic record of this region. On the contrary, these deposits preserved precious evidence of ephemeral stays that preceded the long-lasting Magdalenian occupation of this portion of the German Jura. Possibly aside from Langmahdhalde, a comparable record is not documented in the Swabian Jura, likely due to taphonomic processes (Barbieri et al., 2018, 2021).

Although Lone and Ach valleys in the Swabian Jura were steadily occupied by Magdalenian foragers starting at least from 17/16 ka cal BP (Kind, 2003; Taller, 2014; Taller et al., 2014; Maier et al., 2020; Barbieri et al., 2021), our study confirms that Magdalenian hunter-gatherers settled in the Altmühl Valley only starting 15 ka. Previous research showed that such increase in long-lasting stays resulted from the expansion of the Magdalenian foragers that had occupied the Swabian Jura since 17 ka cal BP (Huber and Floss, 2014; Taller, 2014; Taller et al., 2014; Floss et al., 2015; Maier, 2015; Maier et al., 2020). Despite an increase in paleoenvironmental works in southern Germany (Drucker et al., 2011; Ziegler, 2019; Wong et al., 2020a, 2020b), current hypotheses of a causal link between the Magdalenian dispersal in this region and environmental oscillations have remained mostly based on archives that are located 100s or 1000s km away from the Swabian and Franconian sites (Taller et al., 2014; Maier, 2015; Maier et al., 2020). The human–environment interactions reconstructed with these studies do not have the resolution required to address the later onset of the Magdalenian in the Franconian Jura. By comparing our results with recent works from the Lone Valley (Ziegler, 2019; Barbieri and Miller, 2019a; Wong et al., 2020a, 2020b), we hypothesized that an earlier expansion of Magdalenian foragers into the Franconian Jura was likely prevented by a climatic barrier. In addition, we proposed that the comparatively late Magdalenian dispersal in this region probably followed the eastward expansion of cool temperatures and frequent melting periods. Further work is required to confirm these reconstructions and explore whether this shift in environments represents a regional response to larger-scale climatic oscillations, such as the Heinrich Event 1. The hypothesis of a late onset of this specific environment in South-Eastern Germany emerges also from the comparison of paleoenvironmental archives from Switzerland and the Black and Bavarian Forest (Raab and Völkel, 2003; Ivy-Ochs et al., 2004; Drucker et al., 2012; Rasmussen et al., 2014; Duprat-Oualid et al., 2017; Rey et al., 2020; Reade et al., 2020a, 2020b).

Our study highlighted that different environments, taphonomic processes, and site uses likely coexisted across the German Jura after the LGM. Therefore, it remains fundamental to further expand our regional, multisite data set to reconstruct the recolonization of this region after the LGM.

Declaration of competing interest

The authors declare to have no competing interests.

Acknowledgments

The first author was supported through this work by funding from the Portuguese Ministry for Science and Technology (PTDC/HAR-ARQ/27833/2017) at the Interdisciplinary Center for Archaeology and the Evolution of Human Behaviour (ICArEHB). We would like to thank the owner of Klausennische, the Schneider Hotel & Brauereigasthof GmbH, and especially Josef Schneider, for allowing us to excavate the site. The Bayerisches Landesamt für Denkmalpflege (BLfD) provided administrative help. The excavations were financed by the Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU). We thank the excavation team of Kausennsiche and the owner of Felsenhäusl-Kellerhöhle for granting us access to the site. Thanks also to Flora Schilt for the collection of micromorphological samples and Aristeidis Varis for discussions and information about the lithostratigraphy of Langmahdhalde. We acknowledge Tomás Azevedo and the Light Microscopy Unit of CBMR-UAlg. The Microscopy Unit was partially supported by the Portuguese Ministry for Science and Technology (PPBI-POCI-01-0145-FEDER-022122). Further acknowledgment for Christopher Miller and Panos Kritikakis for the production of the micromorphological samples from Felsenhäusl-Kellerhöhle at the Geoarchaeology Laboratory of the University of Tübingen. Final thanks to the three anonymous reviewers and the Associate Editor Mathieu Duval for their helpful comments and suggestions, which substantially improved the paper.

Author contributions

A.B. conceived the study with the help of A.M. and T.U.; A.B. performed the geoarchaeological fieldwork and analyses, as well as the comparison with paleoenvironmental data from Swabia; T.L. conducted the collection and dating of luminescence samples; C.M. executed the photogrammetric work. A.B. wrote the paper with contributions from A.M., T.L., C.M., M.H., and T.H.

Supplementary Online Material

Supplementary Online Material related to this article can be found at https://doi.org/10.1016/j.jhevol.2022.103267.

References

Aitken, M.J., 1998. An Introduction to Optical Dating: The Dating of Quaternary Sediments by the Use of Photon-Stimulated Luminescence. Oxford Science Publications, Oxford.

Angelucci, D.E., 2010. The recognition and description of knapped lithic artifacts in thin section. Geoarchaeology 25, 220–232.

Antczak-Orlewska, O., Okupny, D., Pawłowski, D., Kotrys, B., Krąpiec, M., Luoto, T.P., Peyron, O., Płóciennik, M., Stachowicz-Rybka, R., Wacnik, A., Szmańda, J.B., Szychowska-Krąpiec, E., Kittel, P., 2022. The environmental history of the oxbow in the Luciąża River valley – Study on the specific microclimate during Allerød and Younger Dryas in central Poland. Quat. Int. (in press) https://www.sciencedirect.com/science/article/pii/S104061822100447X?via%3Dihub.

Banks, W.E., d'Errico, F., Peterson, A.T., Vanhaeren, M., Kageyama, M., Sepulchre, P., Ramstein, G., Lost, A., Lunt, D., 2008. Human ecological niches and ranges during the LGM in Europe derived from an application of eco-cultural niche modeling. J. Archaeol. Sci. 35, 481–491.

Barbieri, A., 2019. Landscape Changes, Cave Site Formation and Human Occupation During the Late Pleistocene: A Geoarchaeological Study from the Ach and Lone Valleys (Swabian Jura, SW Germany). Universitätsbibliothek Publikation, Tübingen.

Barbieri, A., Leven, C., Toffolo, M.B., Hodgins, G.W.L., Kind, C.J., Conard, N.J., Miller, C.E., 2018. Bridging prehistoric caves with buried landscapes in the Swabian Jura (southwestern Germany). Quat. Int. 485, 23–43.

Barbieri, A., Miller, C.E., 2019a. Mikromorphologie. In: Kind, C. (Ed.), Löwenmensch und Mehr Die Ausgrabungen 2008–2013 in den Altsteinzeitlichen Schichten der Stadel-Höhle im Hohlenstein (Lonetal), Gemeinde Asselfingen, Alb-Donau-Kreis. Dr. Ludwig Reichert Verlag, Wiesbaden, pp. 42–44.

Barbieri, A., Miller, C.E., 2019b. Rekonstruktion der Fundplatzgenese der Stadel-Höhle im Hohlenstein. In: Löwenmensch und Mehr Die Ausgrabungen 2008–2013 in den Altsteinzeitlichen Schichten der Stadel-Höhle im Hohlenstein (Lonetal), Gemeinde Asselfingen, Alb-Donau-Kreis. Dr. Ludwig Reichert Verlag, Wiesbaden, pp. 101–112.

Barbieri, A., Bachofer, F., Schmaltz, E.M., Leven, C., Conard, N.J., Miller, C.E., 2021. Interpreting gaps: A geoarchaeological point of view on the Gravettian record of Ach and Lone valleys (Swabian Jura, SW Germany). J. Archaeol. Sci. 127, 105335.

Beck, M., Züchner, C., Feldmann, S., Gehlen, B., Kaulich, B., Rathgeber, T., Tillmann, A., 2006. Wildbeuter in Bayern - Paläo- und Mesolithikum. In: Sommer, C.S. (Ed.), Archäologie in Bayern - Fenster zur Vergangenheit. Pustet, Regensburg, pp. 32–54.

Bertran, P., Texier, J.P., 1999. Facies and microfacies of slope deposits. Catena 35, 99–121.

Beskow, G., 1947. Soil freezing and frost heaving with special application to roads and railroads. Soil Sci. 65, 355.

Birks, H.J.B., Willis, K.J., 2008. Alpines, trees, and refugia in Europe. Plant Ecol. Divers. 1, 147–160.
Birkner, F., 1936. Ur- und Vorgeschichte Bayerns. Verlag Knorr & Hirth, München.
Böhner, U., 2008. Die Schicht E3 der Sesselfelsgrotte und die Funde aus dem Abri I am Schulerloch. Späte Micoquien-Inventare und Ihre Stellung zum Moustérien. Steiner, Stuttgart.
Borger, H., Widdowson, M., 2001. Indian laterites, and lateritious residues of southern Germany: A petrographic, mineralogical, and geochemical comparison. Z. Geomorphol. 45, 177–200.
Bosinski, G., 1967. Die Mittelpaläolithischen Funde im Westlichen Mitteleuropa. Böhlau-Verlag, Köln/Graz.
Campen, I., 1990. Die Sedimente der Höhlen und Abris der Mittleren Schwäbischen Alb und Ihre Klimatische Ausdeutung. Universitätsbibliothek Publikation, Tübingen.
Catt, J.A., 1991. Soils as indicators of Quaternary climatic change in mid-latitude regions. Geoderma 51, 167–187.
Chilingar, G.V., Bissell, H.J., Wolf, K.H., 1967. Diagenesis of carbonate rocks. In: Developments in Sedimentology. Elsevier, Amsterdam, pp. 179–322.
Conard, N.J., Uerpmann, H.-P., 1998. Die Ausgrabungen 1997 und 1998 im Hohle Fels bei Schelklingen, Alb-Donau-Kreis. Archäologische Ausgrabungen in Baden-Württemberg 1998, 47–52.
Conard, N.J., Bolus, M., 2003. Radiocarbon dating the appearance of modern humans and timing of cultural innovations in Europe: New results and new challenges. J. Hum. Evol. 44, 331–371.
Conard, N.J., Malina, M., 2004. Die Ausgrabungen 2004 in den frühen jungpaläolithischen Schichten des Hohle Fels bei Schelklingen, Alb-Donau-Kreis. Archäologische Ausgrabungen in Baden-Württemberg 2004, 17–21.
Conard, N.J., Malina, M., 2005. Neue Ergebnisse zum Mittelpaläolithikum, zum Aurignacien und zu den letzen Neandertalern am Hohle Fels bei Schelklingen, Alb-Donau-Kreis. Archäologische Ausgrabungen in Baden-Württemberg 2005, 17–20.
Conard, N.J., Malina, M., 2007. Die Ausgrabung 2007 im Hohle Fels bei Schelklingen, Alb-Donau-Kreis, und neue Einblicke in die Anfänge des Jungpaläoloithikums. Archäologische Ausgrabungen in Baden-Württemberg 2007, 17–20.
Conard, N.J., Bolus, M., 2008. Radiocarbon dating the late Middle Paleolithic and the Aurignacian of the Swabian Jura. J. Hum. Evol. 55, 886–897.
Conard, N.J., Malina, M., 2008. Spektakuläre Funde aus dem unteren Aurignacien vom Hohle Fels bei Schelklingen, Alb-Donau-Kreis. Archäologische Ausgrabungen in Baden-Württemberg 2008, 19–22.
Conard, N.J., Malina, M., 2010. Neue Belege für Malerei aus dem Magdalénien vom Hohle Fels. Archäologische Ausgrabungen Baden-Württemberg 2009, 52–56.
Conard, N.J., Malina, M., 2012. Neue Forschungen in den Magdalénien-schichten des Hohle fels bei Schelklingen. Archäologische Ausgrabungen in Baden-Württemberg 2011, 56–60.
Conard, N.J., Malina, M., 2013. Grabungen in Schichten des Moustérien und Gravettien im Hohle Fels bei Schelklingen. Archäologische Ausgrabungen in Baden-Württemberg 2012, 78–83.
Conard, N.J., Malina, M., 2014. Eine mögliche zweite Frauen Figurine vom Hohle Fels und Neues zur Höhlennutzung im Mittel- und Jungpaläolithikum. Archäologische Ausgrabungen in Baden-Württemberg 2013, 54–59.
Conard, N.J., Malina, M., 2016. Außergewöhnliche neue Funde aus den aurignacienzeitlichen Schichten vom Hohle Fels bei Schelklingen. Archäologische Ausgrabungen in Baden-Württemberg 2015, 60–66.
Conard, N.J., Janas, A., 2018. Fortsetzung der Ausgrabung am Hohle Fels und die Entdeckung einer markierten Mammutrippe aus dem Gravettien. Archäologische Ausgrabungen in Baden-Württemberg 2017, 52–55.
Conard, N.J., Malina, M., 2020. Fortsetzung der Ausgrabungen am Hohle Fels und neue aurignacienzeitliche Werkzeuge aus Mammutelfenbein. Archäologische Ausgrabungen in Baden-Württemberg 2019, 47–51.
Conard, N.J., Langguth, K., ürpmann, H.-P., 1999. Die Grabungen 1999 in den Gravettien-Schichten des Hohle Fels bei Schelklingen, Alb-Donau-Kreis. Archäologische Ausgrabungen in Baden-Württemberg 1999, 21–25.
Conard, N.J., Langguth, K., Ürpmann, H.-P., 2000. Die Ausgrabungen im Gravettien des Hohle Fels bei Schelklingen, Alb-Donau-Kreis. Archäologische Ausgrabungen in Baden-Württemberg 2000, 18–22.
Conard, N., Langguth, K., Uerpmann, H.-P., 2002. Einmalige Funde aus dem Aurignacien und erste Belege für ein Mittelpaläolithikum im Hohle Fels bei Schelklingen, Alb-Donau-Kreis. Archäologische Ausgrabungen in Baden-Württemberg 2002, 21–27.
Conard, N.J., Langguth, K., ürpmann, H.-P., 2003. Die Ausgrabungen 2003 in den Gravettien und Aurignacien Schichten des Hohle Fels bei Schelklingen, Alb-Donau-Kreis, und die kulturelle Entwicklung im frühen Jungpaläolithikum. Archäologische Ausgrabungen in Baden-Württemberg 2003, 17–22.
Conard, N.J., Janas, A., Zeidi, M., 2015. Neues aus dem Lonetal: Ergebnisse von Ausgrabungen an der Fetzershaldenhöhle und dem Vogelherd. Archäologische Ausgrabungen in Baden-Württemberg 2014, 59–64.
Conard, N.J., Janas, A., Zeidi, M., 2018. Ausgrabungen in den magdalénienzeitlichen Schichten der Langmahdhalde im Lonetal. Archäologische Ausgrabungen in Baden-Württemberg 2017, 55–59.
Conard, N.J., Janas, A., Zeidi, M., 2019. Ausgrabungen an der Langmahdhalde liefern weitere Einblicke in magdalénienzeitliche Lebensweisen auf der Schwäbischen Alb. Archäologische Ausgrabungen in Baden-Württemberg 2018, 60–63.
Conard, N.J., Janas, A., Zeidi, M., 2020. Ausgrabungen an der Langmahdhalde im Lonetal: Raumnutzung und Siedlungsdynamik im Magdalénien. Archäologische Ausgrabungen in Baden-Württemberg 2019, 51–55.
Coutard, J.P., Van Vliet-Lanoe, B., Auzet, A.V., Koster, E.A., French, H.M., 1988. Frost heaving and frost creep on an experimental slope: Results for soil structures and sorted stripes in Periglacial processes and landforms. Z. Geomorphol. Suppl. 71, 13–23.
Dirian, A., 2003. Sesselfelsgrotte V. Das Späte Jungpaläolithikum und das Spätpaläolithikum der Oberen Schichten der Sesselfelsgrotte. Saarbrücker Druckerei und Verlag, Saarbrücken.
Drucker, D.G., Kind, C.-J., Stephan, E., 2011. Chronological and ecological information on Late-glacial and early Holocene reindeer from northwest Europe using radiocarbon (14C) and stable isotope (13C, 15N) analysis of bone collagen: Case study in southwestern Germany. Quat. Int. 245, 218–224.
Drucker, D.G., Bridault, A., Cupillard, C., 2012. Environmental context of the Magdalenian settlement in the Jura Mountains using stable isotope tracking (13C, 15N, 34S) of bone collagen from reindeer (*Rangifer tarandus*). Quat. Int. 272–273, 322–332.
Duprat-Oualid, F., Rius, D., Bégeot, C., Magny, M., Millet, L., Wulf, S., Appelt, O., 2017. Vegetation response to abrupt climate changes in Western Europe from 45 to 14.7k cal BP: The Bergsee lacustrine record (Black Forest, Germany). J. Quat. Sci. 32, 1008–1021.
Fedoroff, N., De Kimpe, C.R., Page, F., Bourbeau, G., 1981. Essai d'interprétation des transferts sous forme figurée dans les podzols du Québec méridional à partir de l'étude micromorphologique des profils. Geoderma 26, 25–45.
Fitzpatrick, E.A., 1980. Soils. Their Formation, Classification and Distribution. Longman, New York.
Floss, H., Hoyer, C.T., Huber, N., 2015. Anthropologie in alten Sammlungen neu Entdeckt: Bemalte und gravierte Steine aus den Klausenhöhlen bei Essing im Altmühltal (Bayern). Anthropologie 53, 257–277.
Freund, G., 1961. Zur Frage paläolithischer Besiedlung der Unteren Klause bei Neu-Essing, Landkreis Kelheim. Germania: Anzeiger der Römisch-Germanischen Kommission des Deutschen Archäologischen Instituts 39, 1–7.
Freund, G., 1984. Die Sesselfelsgrotte im unteren Altmühltal, Landkreis Kelheim. Führer zu Archäeologischen Denkmälern Deutschland 6, 79–89.
Freund, G., 1998. Sesselfelsgrotte I - Grabungsverlauf und Stratigraphie. Saarbrücker Druckerei und Verlag, Saarbrücken.
Freund, G., Reisch, L., 2014. Sesselfelsgrotte VI, Naturwissenschaftliche Untersuchungen Wirbeltierfauna 1. Franz Steiner Verlag, Stuttgart.
Freund, G., Richter, J., 2017. Sesselfelsgrotte VII, Naturwissenschaftliche Untersuchungen Wirbeltierfauna 2-Mollusken-Vegetation. Franz Steiner Verlag, Stuttgart.
Goldberg, P., 1979. Micromorphology of Pech-de-l'Azé II sediments. J. Archaeol. Sci. 6, 17–47.
Gribenski, N., Valla, P.G., Preusser, F., Roattino, T., Crouzet, C., Buoncristiani, J.-F., 2021. Out-of-phase Late Pleistocene glacial maxima in the Western Alps reflect past changes in North Atlantic atmospheric circulation. Geology 49, 1096–1101.
Grimm, S.B., 2019. Resilience and Re-organisation of Social Systems During the Weichselian Lateglacial in Northwest-Europe. An Evaluation of the Archaeological, Climatic, and Environmental Records. Römisch-Germanisches Zentralmuseum, Mainz.
Hattermann, M., Barbieri, A., Uthmeier, T., 2019. Everything lost? Reconstruction of Middle- and Upper Paleolithic occupations at the Felsenhäusl- Kellerhöhle, Lower Altmühl Valley. Quartär 66, 81–110.
Hewitt, G.M., 1996. Some genetic consequences of ice ages, and their role in divergence and speciation. Biol. J. Linn. Soc. 58, 247–276.
Hofmann, F.M., Rauscher, F., McCreary, W., Bischoff, J.-P., Preusser, F., 2020. Revisiting Late Pleistocene glacier dynamics north-west of the Feldberg, southern Black Forest, Germany. E&G Quat. Sci. J. 69, 61–87.
Hornauer-Jahnke, T., 2019. ^{14}C Daten. In: Kind, C. (Ed.), Löwenmensch und Mehr Die Ausgrabungen 2008–2013 in den Altsteinzeitlichen Schichten der Stadel-Höhle im Hohlenstein (Lonetal), Gemeinde Asselfingen, Alb-Donau-Kreis. Dr. Ludwig Reichert Verlag, Wiesbaden, pp. 44–46.
Horwitz, L.K., Goldberg, P., 1989. A study of Pleistocene and Holocene hyaena coprolites. J. Archaeol. Sci. 16, 71–94.
Housley, R.A., Gamble, C.S., Street, M., Pettitt, P., 1997. Radiocarbon evidence for the Lateglacial human recolonisation of Northern Europe. Proc. Prehist. Soc. 63, 25–54.
Huber, N., Floss, H., 2014. Bemalte Steine aus dem Magdalénien der Klausenhöhlen bei Essing (Bayern). Mitt. Ges. Urgesch. 23, 103–119.
Iriondo, M.H., Kröhling, D.M., 2007. Non-classical types of loess. Sediment. Geol. 202, 352–368.
Ivy-Ochs, S., Schäfer, J., Kubik, P.W., Synal, H.-A., Schlüchter, C., 2004. The timing of deglaciation on the northern Alpine foreland (Switzerland). Eclogae Geol. Helv. 97, 47–55.
Ivy-Ochs, S., Kerschner, H., Kubik, P.W., Schlüchter, C., 2006. Glacier response in the European Alps to Heinrich Event 1 cooling: The Gschnitz stadial. J. Quat. Sci. 21, 115–130.
Ivy-Ochs, S., Kerschner, H., Reuther, A., Preusser, F., Heine, K., Maisch, M., Kubik, P.W., Schlüchter, C., 2008. Chronology of the last glacial cycle in the European Alps. J. Quat. Sci. 23, 559–573.
Jochim, M., Herhahn, C., Starr, H., 1999. The Magdalenian colonization of southern Germany. Am. Anthropol. 101, 129–142.
Kaplar, C.W., 1965. Stone migration by freezing of soil. Science 149, 1520–1521.
Kaulich, B., 1994. Die Klausenhöhle. In: Mayer, R.K.F., Schmidt-Kaler, H. (Eds.), Unteres Altmühltal und Weltenburger Enge. Pfeil, München, pp. 81–86.
Kaulich, B., Nadler, M., Reisch, L., 1978. Führer zu urgeschichtlichen Höhlenfundplätzen des unteren Altmühltales. Zusammengestellt für die Tagung der Hugo Obermaier-Gesellschaft 28, 7–52.

Kaulich, B., Weißmüller, W., 2003. Nachuntersuchungen in der Felsenhäusl-Kellerhöhle bei Essing. In: Rind, M.M. (Ed.), Wer Andern eine Grube Gräbt…. Faustus, Büchenbach, pp. 29–33.
Kemp, R.A., 1999. Micromorphology of loess-paleosol sequences: A record of paleoenvironmental change. Catena 35, 179–196.
Kind, C., 2003. Die absolute Datierung des Magdaleniens und des Mesolithikums in Süddeutschland. Veröffentlichungen des Landesamtes für Archäologie 57, 303–319.
Kind, C., 2019. Löwenmensch und Mehr Die Ausgrabungen 2008–2013 in den Altsteinzeitlichen Schichten Der Stadel-Höhle im Hohlenstein (Lonetal), Gemeinde Asselfingen, Alb-Donau-Kreis. Dr. Ludwig Reichert Verlag, Wiesbaden.
Kind, C.J., Ebinger-Rist, N., Wolf, S., Beutelspacher, T., Wehrberger, K., 2014. The smile of the Lion Man. Recent excavations in Stadel Cave (Baden-Wurttemberg, south-western Germany) and the restoration of the famous upper Palaeolithic figurine. Quartär 61, 129–145.
Kolobova, K.A., Chabai, V.P., Shalagina, A.V., Krajcarz, M.T., Krajcarz, M., Rendu, W., Vasiliev, S.V., Markin, S.V., Krivoshapkin, A.I., 2019. Exploitation of the natural environment by Neanderthals from Chagyrskaya Cave (Altai). Quartär 66, 7–31.
Kozłowski, S.K., Połtowicz-Bobak, M., Bobak, D., Terberger, T., 2012. New information from Maszycka cave and the Late Glacial recolonisation of Central Europe. Quat. Int. 272–273, 288–296.
Küßner, M., Terberger, T., 2006. Die Fundstelle Gera-Zoitzberg und die Zeit zwischen Gravettien und Magdalénien in Mitteldeutschland. Alt-Thüringen 39, 69–120.
Maier, A., 2015. The Central European Magdalenian. Springer, Dordrecht.
Maier, A., 2017. Population and settlement dynamics from the Gravettian to the Magdalenian. Mitt. Ges. Urges. 26, 83–102.
Maier, A., Liebermann, C., Pfeifer, S.J., 2020. Beyond the Alps and Tatra Mountains—the 20–14 ka repopulation of the Northern Mid-latitudes as inferred from palimpsests deciphered with keys from Western and Central Europe. J. Paleolit. Archaeol. 3, 398–452.
Mestdagh, H., 2005. Environmental Reconstruction of the Last Interglacial and Early Glacial based on Soil Characteristics of Pedocomplexes on Loess at Selected Sites from the Atlantic Coast to Central Asia. Ph.D. Dissertation, University of Gent.
Miller, C.E., 2015. A Tale of Two Swabian Caves. Geoarchaeological Investigations at Hohle Fels and Geißenklösterle. Kerns Verlag, Stuttgart.
Monegato, G., Scardia, G., Hajdas, I., Rizzini, F., Piccin, A., 2017. The Alpine LGM in the boreal ice-sheets game. Sci. Rep. 7, 2078.
Müller-Beck, H., 1957. Das Obere Altpaläolithikum in Süddeutschland: Ein Versuch zur Ältesten Geschichte des Menschen. Rudolf Habelt Verlag, Bonn.
Müller, S., Tarasov, P.E., Hoelzmann, P., Bezrukova, E.V., Kossler, A., Krivonogov, S.K., 2014. Stable vegetation and environmental conditions during the Last Glacial Maximum: New results from Lake Kotokel (Lake Baikal region, southern Siberia, Russia). Quat. Int. 348, 14–24.
Nerudová, Z., Doláková, N., Novák, J., 2016. New information augmenting the picture of local environment at the LGM/LGT in the context of the Middle Danube region. Holocene 26, 1345–1354.
Obermaier, H., 1904. Le quaternaire des alpes et la nouvelle classification du Professor Albrecht Penck. L'Anthropologie 15, 25–36.
Obermaier, H., Wernert, P., 1914. Paläolithbeiträge aus Nordbayern. Mitt. Anthropol. Ges. Wien 14, 44–62.
Obermaier, H., Fraunholz, J., 1926. Eine Mammutdarstellung aus Süddeutschland. Jahrbuch für Prähistorische und Ethnographische Kunst 3, 29–32.
Obermaier, H., Wernert, P., 1929. Alt-Paläolithiküm mit Blatt-Typen. Mitt. Anthropol. Ges. Wien 59, 293–310.
Otte, M., 1992. Processus de diffusion à long terme au Magdalénien. In: Rigaud, J.-P. (Ed.), Le Peuplement Magdalénien. Actes du Colloque de Chancelade 1988. Editions du CTHS, Paris, pp. 399–416.
Pasda, C., 1998. Archäologie im Südwesten. Wildbeuter im Archäologischen Kontext-Das Paläolithikum in Südbaden. Folio-Verlag, Bad Bellingen.
Pasda, C., 2010. Palaeolithic humans and the wilderness myth. In: Połtowicz-Bobak, M., Bobak, D. (Eds.), The Magdalenian in Central Europe. New Finds and Concepts. Instytut Archeologii Uniwersytetu Rzeszowskiego, Rzeszów, pp. 101–111.
Pissart, A., 1969. Le mécanisme périglaciaire dressant les pierres dans le sol. Résultats d'expériences. C. R. Acad. Sci. D 268, 3015–3017.
Posth, C., Renaud, G., Mittnik, A., Drucker, D.G., Rougier, H., Cupillard, C., Valentin, F., Thevenet, C., Furtwängler, A., Wißing, C., Francken, M., Malina, M., Bolus, M., Lari, M., Gigli, E., Capecchi, G., Crevecoeur, I., Beauval, C., Flas, D., Germonpré, M., Van Der Plicht, J., Cottiaux, R., Gély, B., Ronchitelli, A., Wehrberger, K., Grigorescu, D., Svoboda, J., Semal, P., Caramelli, D., Bocherens, H., Harvati, K., Conard, N.J., Haak, W., Powell, A., Krause, J., 2016. Pleistocene mitochondrial genomes suggest a single major dispersal of non-africans and a late glacial population turnover in Europe. Curr. Biol. 26, 827–833.
Powers, M.C., 1953. A new roundness scale for sedimentary particles. J. Sediment. Res. 23, 117–119.
Raab, T., Völkel, J., 2003. Late Pleistocene glaciation of the Kleiner Arbersee area in the Bavarian Forest, south Germany. Quat. Sci. Rev. 22, 581–593.
Rasmussen, S.O., Bigler, M., Blockley, S.P., Blunier, T., Buchardt, S.L., Clausen, H.B., Cvijanovic, I., Dahl-Jensen, D., Johnsen, S.J., Fischer, H., Gkins, V., Guillevic, M., Hoek, W.Z., Lowe, J.J., Pedro, J.B., Popp, T., Seierstad, I.K., Steffensen, J.P., Svensson, A.M., Vallelonga, P., Vinther, B.M., Walker, M.J.C., Wheatley, J.J., Winstrup, M., 2014. A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: Refining and extending the INTIMATE event stratigraphy. Quat. Sci. Rev. 106, 14–28.
Rathgeber, T., 2006. Fossile Menschenreste aus der Sesselfelsgrotte im unteren Altmühltal (Bayern, Bundesrepublik Deutschland). Quartär 54, 33–59.
Reade, H., Tripp, J.A., Charlton, S., Grimm, S., Sayle, K.L., Fensome, A., Higham, T.F.G., Barnes, I., Stevens, R.E., 2020a. Radiocarbon chronology and environmental context of Last Glacial Maximum human occupation in Switzerland. Nat. Sci. Rep. 10, 4694.
Reade, H., Tripp, J., Charlton, S., Grimm, S.B., Leesch, D., Müller, W., Sazle, K.,L., Fensome, S.A., Higham, T.F.G., Barnes, I., Stevens, R.E., 2020b. Deglacial landscapes and the late Upper Palaeolithic of Switzerland. Quat. Sci. Rev. 239, 106372.
Reuther, A.U., Fiebig, M., Ivy-Ochs, S., Kubik, P.W., Reitner, J.M., Jerz, H., Heine, K., 2011. Deglaciation of a large piedmont lobe glacier in comparison with a small mountain glacier – new insight from surface exposure dating. Two studies from SE Germany. E&G Quat. Sci. J. 60, 248–269.
Rey, F., Gobet, E., Schwörer, C., Hafner, A., Schwöre, C., Tinner, W., 2020. Climate impacts on vegetation and fire dynamics since the last deglaciation at Moossee (Switzerland). Clim. Past 16, 1347–1367.
Richter, J., 2002. Die 14 C-Daten aus der Sesselfelsgrotte und die Zeitstellung des Micoquien/M.M.O. Germania: Anzeiger der Römisch-Germanischen Kommission des Deutschen Archäologischen Instituts 80, 1–22.
Richter, D., Mauz, B., Böhner, U., Weismüller, W., Wagner, G.A., Freund, G., Rink, W.J., Richter, J., 2000. Luminescence dating of the Middle/Upper Palaeolithic sites "Sesselfelsgrotte" and "Abri I Schulerloch", Altmühltal, Bavaria. In: Orschiedt, J., Weniger, C. (Eds.), Neanderthals and Modern Humans – Discussing the Transition. Central and Eastern Europe from 50.000–30.000 B.P. Neanderthal Museum, Mettmann, pp. 30–41.
Riek, G., Heller, F., 1957. Drei Jungpaläolithische Stationen am Bruckersberg in Giengen an der Brenz. Verlag Silberburg – Kommissionsverlag, Stuttgart.
Riek, G., Gieseler, W., Czarnetzki, A., 1973. Das Paläolithikum der Brillenhöhle bei Blaubeuren. Verlag Müller und Gräff, Stuttgart.
Romans, J.C.C., Stevens, J.H., Robertson, L., 1966. Alpine soils of north-east Scotland. J. Soil Sci. 17, 184–199.
Romans, J.C.C., Robertson, L., Dent, D.L., 1980. The micromorphology of young soils from south-east Iceland. Geogr. Ann. Phys. Geogr. 62, 93–103.
University of Gent Sanz, M., Daura, J., Égüez, N., Brugal, J.-P., 2016. Not only hyenids: a multi-scale analysis of Upper Pleistocene carnivore coprolites in Cova del Coll Verdaguer (NE Iberian Peninsula). Palaeogeogr. Palaeoclimatol. Palaeoecol. 443, 249–262.
Schiegl, S., Goldberg, P., Pfretzschner, H., Conard, N.J., 2003. Paleolithic burnt bone horizons from the Swabian Jura: Distinguishing between in situ fireplaces and dumping areas. Geoarchaeology 18, 541–565.
Schmieder, M., Kennedy, T., Jourdan, F., Buchner, E., Reimold, W.U., 2018. A high-precision 40Ar/39Ar age for the Nördlinger Ries impact crater, Germany, and implications for the accurate dating of terrestrial impact events. Geochem. Cosmochim. Acta 220, 146–157.
Schoch, E.O., 1973. Fossile Menschenreste: Der Weg zum Homo sapiens. N. Brehm-Bücherei, Lutherstadt Wittenberg.
Steguweit, L., 2011. Neue paläolithische Funde aus Bayern. Fines Transire 20, 43–52.
Stoops, G., 2021. Guidelines for Analysis and Description of Soil and Regolith Thin Sections. John Wiley & Sons, Hoboken.
Street, M., Terberger, T., Orschiedt, J., 2006. A critical review of the German Paleolithic hominin record. J. Hum. Evol. 51, 551–579.
Svoboda, J., Van der Plicht, H., Kuželka, V., 2002. Upper Palaeolithic and Mesolithic human fossils from Moravia and Bohemia (Czech Republic): Some new 14C dates. Antiquity 76, 957–962.
Taller, A., 2014. Das Magdalénien des Hohle Fels. Chronologische Stellung, Lithische Technologie und Funktion der Rückenmesser. Kerns Verlag, Tübingen.
Taller, A., Bolus, M., Conard, N.J., 2014. The Magdalenian of Hohle Fels and the resettlement of the Swabian Jura after the LGM. In: Otte, M., Le Brun-Ricalens, F. (Eds.), Modes de Contacts et de Déplacements au Paléolithique Eurasiatique - Modes of Contact and Displacements During the Eurasian Palaeolithic, Actes du Colloque International de la Commission 8 (Paléolithique supérieur) de l'UISPP. Université de Liège, Liège, pp. 383–402.
Terberger, T., 2003. Vom Gravettien zum Magdalénien in Mitteleuropa: Aspekte der menschlichen Besiedlungsgeschichte in der Zeit um das zweite Kältemaximum der letzten Eiszeit. Archäol. Nachr. 8, 55–62.
Terberger, T., 2008. Andreas Dirian, Sesselfelsgrotte V. Das späte Jungpaläolithikum und das Spätpaläolithikum der oberen Schichten der Sesselfelsgrotte. Germania: Anzeiger der Römisch-Germanischen Kommission des Deutschen Archäologischen Instituts 86, 770–775.
Terberger, T., Street, M., 2002. Hiatus or continuity? New results for the question of pleniglacial settlement in Central Europe. Antiquity 76, 691–698.
Tóth, E.G., Köbölkuti, Z.A., Pedryc, A., Höhn, M., 2017. Evolutionary history and phylogeography of Scots pine (*Pinus sylvestris* L.) in Europe based on molecular markers. J. For. Res. 28, 637–651.
Ufrecht, W., 2008. Evaluating landscape development and karstification of the central Schwäbische Alb (Southwest Germany) by fossil record of karst fillings. Z. Geomorphol. 52, 417–436.
Uthmeier, T., Bandasch, L., Hohenester, I., Meis, L., Stiller, L., 2019. Auf den Spuren der verschollenen Kratzer - Nachgrabungen in den Klausenhöhlen bei Essing, Landkreis Kelheim, Niederbayern. Archäologisches Jahr in Bayern 2018, 9–11.
Valoch, K., 1996. Le Paléolithique en Tchéquie et en Slovaquie. Jérome Millon, Grenoble.
Van Vliet-Lanoë, B., 1988. Le Rôle de la Glace de Ségrégation Dans les Formations Superficielles de l'Europe de l'Ouest. Editec, Caen.

Van Vliet Lanoë, B., 1976. Traces de segregation de galce en lentilles associees aux sols et phenomenes periglaciaires fossiles. Biul. Peryglac. 26, 42–55.
Van Vliet-Lanoë, B., Fox, C.A., 2018. Frost action. In: Stoops, G., Marcelino, V., Mees, F. (Eds.), Interpretation of Micromorphological Features of Soils and Regoliths. Elsevier, Amsterdam, pp. 575–603.
Verpoorte, A., 2009. Limiting factors on early modern human dispersals: The human biogeography of late Pleniglacial Europe. Quat. Int. 201, 77–85.
Vos, C., Don, A., Prietz, R., Heidkamp, A., Freibauer, A., 2016. Field-based soil-texture estimates could replace laboratory analysis. Geoderma 267, 215–219.
Weißmüller, W., 1995. Sesselfelsgrotte II. Die Silexartefakte der Unteren Schichten der Sesselfelsgrotte. Ein Beitrag zum Problem des Moustérien. Saarbrücker Druckerei und Verlag, Saarbrücker.
Wolff, W., 1962. Periglazial-Erscheinungen auf der Albhochfläche. Karl Mayer KG, Stuttgart.
Wong, G.L., Drucker, D.G., Starkovich, B.M., Conard, N.J., 2020a. Latest Pleistocene paleoenvironmental reconstructions from the Swabian Jura, southwestern Germany: Evidence from stable isotope analysis and micromammal remains. Palaeogeogr. Palaeoclimatol. Palaeoecol. 540, 109527.
Wong, G.L., Starkovich, B.M., Drucker, D.G., Conard, N.J., 2020b. New perspectives on human subsistence during the Magdalenian in the Swabian Jura, Germany. Archaeol. Anthropol. Sci. 12, 1–31.
Wright, J.S., 2001. Desert loess versus glacial loess: Quartz silt formation, source areas and sediment pathways in the formation of loess deposits. Geomorphology 36, 231–256.
Ziegler, R., 2019. Kleinsäuger. In: Kind, C. (Ed.), Löwenmensch und Mehr Die Ausgrabungen 2008–2013 in den Altsteinzeitlichen Schichten der Stadel-Höhle im Hohlenstein (Lonetal), Gemeinde Asselfingen, Alb-Donau-Kreis. Dr. Ludwig Reichert Verlag, Wiesbaden, pp. 57–63.
Zingg, T., 1935. Beitrag zur Schotteranalyse. Ph.D. Dissertation, ETH Zurich.