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Interpreting gaps: A geoarchaeological point of view on the Gravettian record of Ach and Lone valleys (Swabian Jura, SW Germany)

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ABSTRACT

Unlike other Upper Paleolithic industries, Gravettian assemblages from the Swabian Jura are documented solely in the Ach Valley (35-30 Kcal BP). On the other hand, traces of contemporaneous occupations in the nearby Lone Valley are sparse. It is debated whether this gap is due to a phase of human depopulation, or taphonomic issues related with landscape changes.

In this paper we present ERT, EC-logging and GPR data showing that in both Ach and Lone valleys sediments and archaeological materials eroded from caves and deposited above river incisions after 37-32 Kcal BP. We argued that the rate of cave erosion was higher after phases of downcutting, when hillside erosion was more intensive. To investigate on the causes responsible for the dearth of Gravettian materials in the Lone Valley we test two alternative hypotheses: i) Gravettian humans occupied less intensively this part of the Swabian Jura. ii) Erosion of cave deposits did not occur at the same time in the two valleys. We conclude that the second hypothesis is most likely. Ages from the Lone Valley show increasing multimillennial gaps between 36 and 18 Kcal BP, while a similar gap is present in the Ach Valley between 28 and 16 Kcal BP. Based on geoarchaeological data from previous studies and presented in this paper, we interpreted these gaps in radiocarbon data as indicating of cave erosion. Furthermore, we argued that the time difference across the two valleys show that the erosion of cave deposits began and terminated earlier in the Lone Valley, resulting in a more intensive removal of Gravettian-aged deposits. The hypothesis that cave erosion was triggered by regional landscape changes seems to be supported by geochronological data from the Danube Valley, which show that terrace formation at the end of the Pleistocene moved westwards throughout southern Germany with a time lag of few millennia.

1. Introduction

1.1. Human behaviors vs taphonomic issues

In archaeology hypotheses regarding changes in human behaviors and environments are based on the interpretation of both actual evidence and missing data (Wallach 2019). The latter are referred to as “gaps” or “hiatus” and, for the most part, they consist in the absence of archaeological materials dating to specific time periods. Although common in archaeological stratigraphies from any region and time period, some gaps have been related with major evolutionary changes of our species. For example, the presence as well as the lack of hominin fossils and archaeological materials in sites located in Levant and Eurasia has been used to reconstruct roots and timing of the dispersal and extinction of human groups out of Africa (i.e., Bar-Yosef and Belfer-Cohen 2001; López et al., 2015). Gaps in the Middle Palaeolithic sequences of North-Western Europe have been interpreted as evidence for the interspersed regional extinction of Neanderthal groups (Hublin

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and Roebroeks 2009). The near lack of human settlements dating to the end of the Bronze Age in Eastern Mediterranean regions has been regarded as the result of long-lasting drought, human migrations and increasing warfare (i.e., Kaniewski et al., 2013; Knapp and Manning 2016). These hiatus, as many others, have been interpreted as the result of a complex interaction between changes in ecology, population density and human migrations. On the other hand, not all the gaps in archaeological records have been interpreted in this fashion. More recent investigations showed that the hiatus between Mesolithic and Neolithic occupations inside rockshelters and caves along the Mediterranean coasts is due to taphonomic issues (Berger 2005; Mlekuž et al., 2008; Berger and Guilaine 2009) and not to human abandonment as previously argued (Biagi and Spataro 2001; Thissen 2005). Similarly, geomorphological research showed that the Holocene record of human occupations in the middle Rhône valley resulted from complex fluvial dynamics, which led to a differential preservation of the sites (Berger 2005, 2011), and it is not related with changes in settlement strategy (Garcia 1993; D'Anna et al., 1993; Py 1993).

Caves located in Ach and Lone Valleys of the Swabian Jura (South West Germany) show evidence of intensive human occupation and, at the same time, exhibit multiple gaps. Among the others, two are the most important. The first hiatus consists of a nearly sterile deposit separating late Middle Paleolithic from early Aurignacian occupations at the site of Hohle Fels and Geißenklösterle, in the Ach Valley (Conard and Bolus 2003, 2008; Miller 2015). Based on such discontinuity in the human use of the caves it has been argued that Neanderthals and Modern Humans did not meet in the Swabian Jura (Conard 2003; Conard and Bolus 2003, 2008; Conard et al., 2006). The second mayor hiatus in the caves of this region consists in the near lack of materials and sediments dating between the Gravettian (35-30 Kcal BP) and Magdalenian (17-14 Kcal BP) occupations. This gap appears even wider in the Lone Valley, where evidence dating to the Gravettian is sparser. In this paper we investigate whether this hiatus is related with a phase of de-population as seen during the transition from Middle to Upper Paleolithic, or whether it is more reflective of taphonomic processes associated with dramatic landscape changes that shaped the Swabian Jura at the end of the Last Ice Age.

1.2. *Evidence of human occupation between 35 Kcal BP and 14 Kcal BP in the Ach and Lone valleys*

The Swabian Jura (*SJ* in Fig. 1) is a mountain range located in South-West Germany, bordered by the Nördlinger Ries crater to the east (*NR* in Fig. 1), the Black Forest to the west (*BF* in Fig. 1), and the Neckar and Danube rivers to the North and South, respectively (Fig. 1). Due to the wide-spread occurrence of limestone bedrock, this region is rich in karstic features, such as dry valleys, dolines, caves, and rock shelters.

The cave sites of the Ach and Lone Valleys have been the focus of intensive archaeological investigation since the 19th century, due to their deep stratigraphic sequences and rich assemblages of Middle and Upper Paleolithic artifacts (for more information about the caves and their settings see section 1 in SI1). In particular, these caves are widely known for their spectacular Aurignacian finds (42-35 Kcal BP[1]), which document the early arrival of modern humans into Central Europe and include some of the earliest evidence for music, art, and religion (Münzel et al., 2002; Conard 2009; Conard and Bolus 2008; Conard et al. 2006, 2009; Higham et al., 2012; Kind et al., 2014; Wolf 2015). Several of the cave sites also contain evidence for intensive occupation during both the Gravettian and Magdalenian. However, while the Magdalenian occupations, dating between 14 Kcal BP and 17 Kcal BP (Kind 2003; Conard and Bolus 2003, 2008; Taller 2015; Hornauer-Jahnke 2019b), are widespread across the region, Gravettian-aged materials are generally absent from the Lone Valley and limited to only a few sites in the Ach Valley.

In the Ach Valley, Geißenklösterle (*GK* in Fig. 1) and Hohle Fels (*HF* in Figs. 1 and 2) have been extensively investigated with modern excavation techniques and intensively dated with radiocarbon and luminescence methods (Richter et al., 2000; Conard and Bolus 2003, 2008; Higham et al., 2012). At Geißenklösterle, Moreau (2009b, 2010) identified 4113 Gravettian lithic artifacts from deposits dating between 37 Kcal BP and 30 Kcal BP (AH I, Conard and Bolus, 2008; Higham et al., 2012). From Hohle Fels, Taller and Conard (2016) reported a Gravettian assemblage, which is composed of 12,830 lithic artifacts, and faunal remains dating between 35 Kcal BP and 31 Kcal BP (AH IIb, IIc, IIcf). The hypothesis that the Gravettian assemblages from Geißenklösterle and Hohle Fels were produced by the same group of humans is supported by the refitting of lithics across the two sites (Taller et al., 2019).

The other caves of the Ach Valley (Brillenhöhle and Sirgenstein) and those of the Lone Valley (Hohlenstein, Bockstein, Vogelherd) were extensively excavated before the 1970s (Fraas 1862; Schmidt 1912; Riek 1934, 1973; Wetzel 1958, 1961, Wetzel and Bosinski, 1969). The archaeologists, who led these early investigations, considered the Gravettian as an archaeological unit which was part of the Aurignacian (Conard and Moreau 2004) and removed almost all intact Pleistocene deposits from these cave sites.

Re-evaluation of lithic materials from these early excavations led to the identification of 706 Gravettian artifacts from the deposits AH V-VII of Brillenhöhlen (*BH* in Fig. 1. Riek 1973; Conard and Moreau 2004; Moreau 2009b; Moreau 2010), and about 30 diagnostic Gravettian tools from the deposits AH II-III of Sirgenstein (*SI* in Fig. 1. Conard and Moreau, 2004). Lithics from these assemblages refit Gravettian materials from Hohle Fels and Geißenklösterle (Scheer 1986, 1990, 1993; Moreau 2009a; Taller et al., 2019), and were found together with faunal materials dating to 34-31 Kcal BP (Conard and Moreau, 2004; Moreau 2009b, 2010; Moreau 2009b).

Despite more recent studies, the occurrence of Gravettian occupations in the cave sites of the Lone Valley remains to be confirmed (Taller et al., 2019). Re-analysis of the small Upper Paleolithic assemblages recovered from Hohlenstein-Stadel (*HS* in Fig. 1) by Wetzel (1961) confirms the absence of materials indicative of Gravettian occupation at this site (Kind 2019a). Excavations conducted with modern techniques at the entrance of this cave, however, uncovered a deposit (layer *KKS*, Fig. 3) containing eight undiagnostic Upper Paleolithic stone tools. Since the latter were associated with faunal remains exhibiting mixed dating, ranging from 27 to 15 Kcal BP, it is not clear whether this assemblage reflects a phase of human occupation prior to or contemporaneous with the Magdalenian (Hornauer-Jahnke 2019a, b). Re-evaluation of lithic artifacts from the site of Bockstein-Törle (*BK* in Fig. 1) detected the presence of a small potential Gravettian assemblage, which is composed at least of four backed pieces from the layers AH IV, V and VI (Borges de Magalhães 2000; Taller et al., 2019). These materials were associated with faunal remains dating between 34 and 25 Kcal BP (Conard and Bolus 2003). So far, no complete up-to-date analysis has been performed on the rich Aurignacian and Magdalenian lithic assemblages recovered by Riek (1934) from Vogelherd (Taller et al., 2019. *VG* in Fig. 1). Nevertheless, radiocarbon dating performed on four faunal remains from the deposits assigned to the Aurignacian (AH V) and the Magdalenian (AH IV and III, Riek, 1934) yielded ages between 34 Kcal BP and 30 Kcal BP (Conard et al., 2003; Conard and Bolus 2003; Conard and Moreau 2004). These dates fall in the Gravettian time period as published for the Ach Valley (Conard and Bolus 2008; Higham et al., 2012; Taller 2015). Two of these bone fragments exhibit evidence of human modifications (KIA 8957 in Conard and Moreau 2004, and KIA, 19542 in Conard et al., 2003). Thus, it is reasonable to conclude that humans visited this site at least sporadically between 34 and 30 kcal BP.

Further evidence of human presence in the Lone Valley between the Aurignacian and Magdalenian comes from the site of Fetzershaldenhöhle (*FH* in Fig. 1). At this rock shelter few undiagnostic stone

[1] All Kcal BP ages reported in this work are AMS dates, calibrated with the online software OxCal 4.4 - IntCal 20 calibration curve.

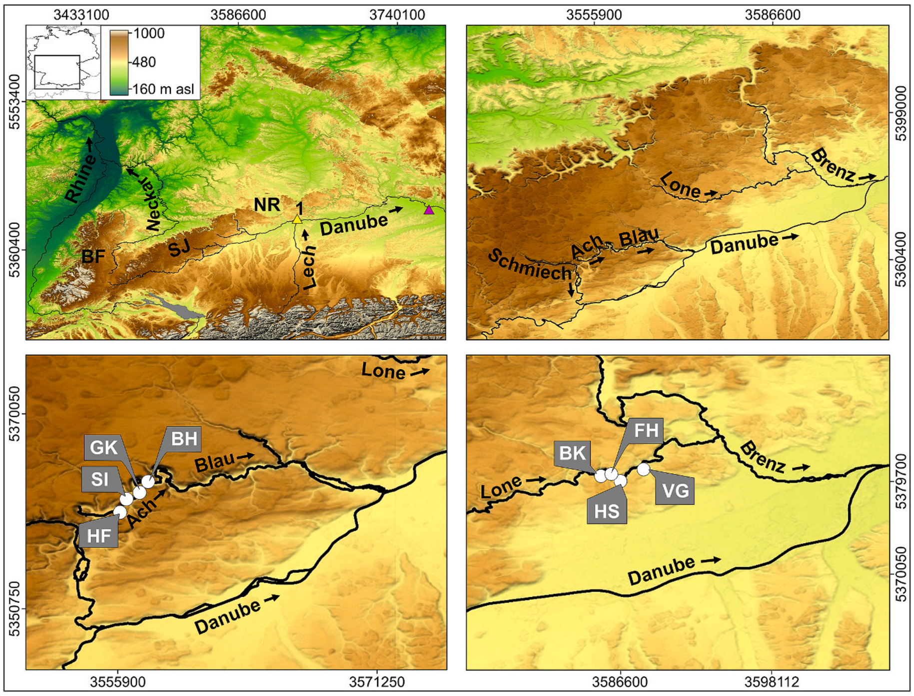

Fig. 1. Region of study. Upper left, general overview of South Germany. ***SJ***, Swabian Jura; ***BF***, Black Forest; ***NR***, Nördlinger Ries; ***1***, area investigated by Schielein (et al., 2011); ***2***, area investigated by Schellmann (2010). **Upper right**, main north tributaries of the Danube River in the Swabian Jura. **Lower left**, the Ach Valley and its main cave sites; ***HF***, Hohle Fels; ***SI***, Sirgenstein; ***GK***, Geißenklösterle; ***BH***, Brillenhöhle. **Lower right,** the Lone Valley and the cave sites mentioned in the text; ***BK***, Bockstein; ***HS***, Hohlenstein-Stadel; ***VG***, Vogelherd; ***FH***, Fetzershaldenhöhle.

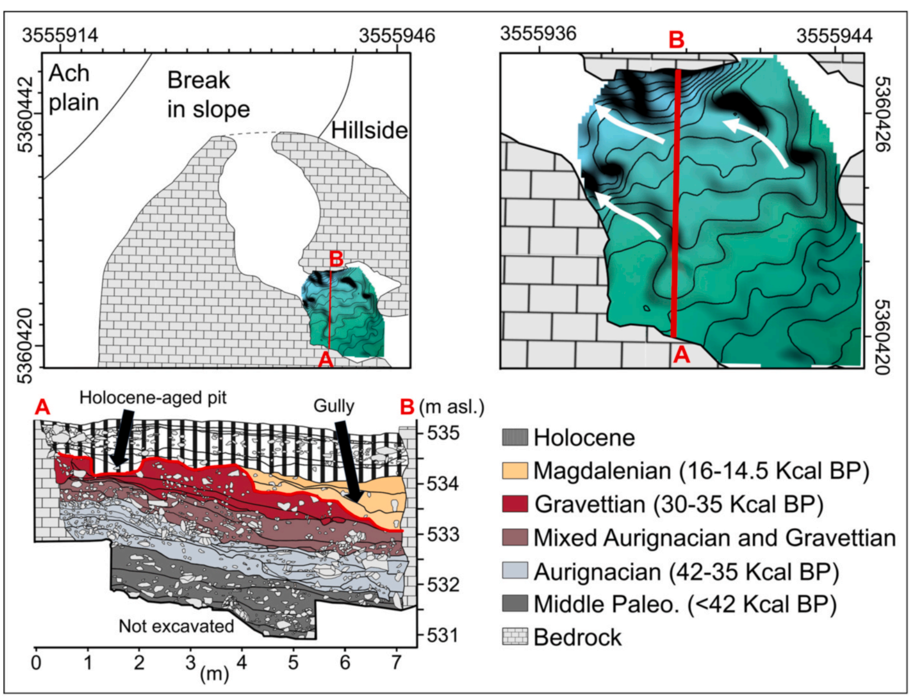

Fig. 2. Gullies infilled with Magdalenian deposits inside Hohle Fels, in the Ach Valley. Upper left, location of the excavated erosional surface separating Gravettian from Magdalenian deposits inside Hohle Fels (maps projected in the DHDN-Gauss-Krüger coordinate system). **Upper right**, topography of the erosional surface. White arrows show location and orientation of main gullies. **Lower half,** drawing of profile 10 from the excavation area. Gravettian deposits are depicted in red, Magdalenian in light orange. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

tools and rare Middle Paleolithic artifacts were deposited together with faunal remains exhibiting evidence of human modification (GH2 and GH3, Conard and Zeidi 2014; Conard et al., 2015; Lykoudi 2018, Benjamin Schuerch, personal communication 2020). Six of these bones dated between 20 Kcal BP and 31 Kcal BP (See SI2), while two fragments yielded ages extending beyond the limit of radiocarbon.

Based on the more abundant archaeological remains dating between 35 Kcal BP and 30 Kcal BP from the Ach Valley, N. Conard and L. Moreau have suggested that Gravettian groups possibly preferred this valley to the Lone Valley (Conard and Moreau 2004; Moreau 2010). Furthermore, a number of researchers have regarded the lower amount of archaeological materials dating between 30 Kcal BP and 16 Kcal BP from both valleys as indicative of a phase of human abandonment, likely induced by deteriorating environmental conditions during the Last Glacial Maximum (LGM) (Jochim at al. 1999, Terberger and Street 2002; Kind 2003; Terberger 2003; Küßner and Terberger 2006; Maier 2015).

1.3. Geomorphological processes and preservation of cave deposits between 35 Kcal BP and 16 Kcal BP

Geoarchaeological studies, however, show that the archaeological

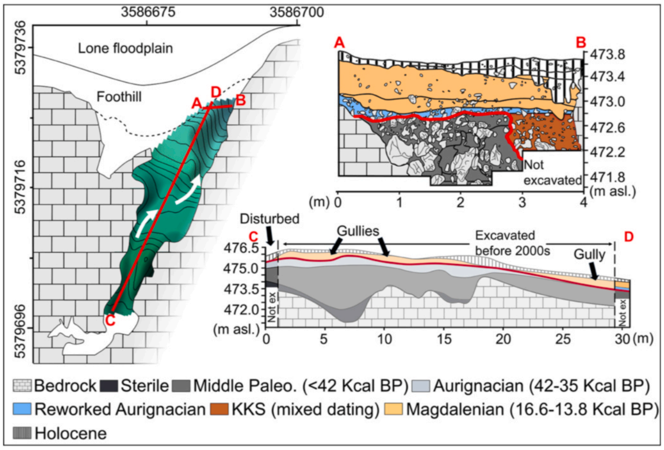

Fig. 3. Gully infilled with Magdalenian deposits inside Hohlenstein-Stadel, in the Lone Valley. On the left, topography of the erosional surface covered with Magdalenian deposits (map projected in the DHDN-Gauss-Krüger (EPSG: 31467) coordinate system, and based on drawings from Wetzel 1961, Beck 1999, Hornauer-Jahnke 2019a, b and Kind 2019b). **Upper right**, section from the 2008–2009 excavation conducted at the dripline of Hohlenstein-Stadel (modified from Hornauer-Jahnke 2019a). Red line shows the surface depicted on the left. **Lower right**, cross-section showing geometry of main deposits (based on drawings from Wetzel 1961, Beck 1999, Hornauer-Jahnke 2019a, b and Kind 2019b). Red line shows the erosional surface reconstructed on the left. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

record from the Swabian Jura dating between 35 and 16 Kcal BP has been shaped by intensive post-depositional processes (Campen 1990, Goldberg et al., 2003, Miller 2015, Barbieri et al., 2018, Barbieri and Miller 2019a, b). In particular, at Hohle Fels mass-wasting led to mixing and stratigraphic inversions in the late Aurignacian and Gravettian deposits (Miller 2015; Taller and Conard 2016). Subsequently, during an intensive phase of erosion, the whole Gravettian sequence was incised by multiple gullies (Fig. 2). These erosive features were later filled with sediments coming from the external hillside (Barbieri et al., 2018; Barbieri 2019), which buried Magdalenian materials dating ca. 16–14.5 Kcal BP (Taller 2015. Fig. 2).

Similar processes took place in the Lone Valley, where one gully extensively removed *in situ* Aurignacian deposits from the dripline area of Hohlenstein-Stadel (Fig. 3. Hornauer-Jahnke 2019a, b). This erosive feature was filled with sediment (*KKS*, Fig. 3) containing undiagnostic Upper Paleolithic stone tools, and faunal remains dating to the late Pleniglacial (27.8 Kcal BP) and Late Glacial (17-15 Kcal BP. Hornauer-Jahnke 2019a, b, c). Mass-wasting processes covered this infilling with Aurignacian materials eroding from the back of the cave (Barbieri and Miller 2019b. Hornauer-Jahnke 2019a, b). Lastly, reworked loess and gravel (*Bergkies*), coming from the external hillslope buried rare Magdalenian materials dating 16.6–13.8 Kcal BP (Barbieri and Miller 2019a, b, Hornauer-Jahnke 2019a, b, c).

Furthermore, coring confirmed the presence of grains of phosphatized loess, fragments of speleothems and bones downslope from the sites of Bockstein (BK in Fig. 1) and Hohle Fels, which Barbieri et al. (2018 and Barbieri 2019) interpreted as deriving from the erosion of cave sediments after 37-32 Kcal BP (A, B, C, D in Fig. 4.). Other data from coring (Schneidermeier 1999) and test pitting conducted downslope from Hohlenstein-Stadel (Bolus et al., 1999, *Exc.* in Fig. 5) revealed unmodified cave bear remains which likely eroded from this cave (Kitagawa 2014; Geiling et al., 2015; Barbieri 2019).

Eroded cave sediments, reworked soil materials, and cryoturbation features are found stratigraphically above fluvial incisions in both the Ach and Lone valleys (Barbieri et al., 2018; Barbieri 2019). In previous publications we argued that this phase of valley incision and subsequent de-vegetation, related with the onset of the LGM, may have triggered erosion within the caves (Barbieri et al., 2018; Barbieri 2019). The dataset we presented in this paper allows for a more precise comparison of valley infillings across the study region, and thus provides ground for testing further hypotheses regarding the dissimilar preservation of the Gravettian record in the Swabian Jura.

2. Methods

The dataset we present in this paper consists of seven Electrical Resistivity Tomography (ERT) profiles, two Electrical Conductivity (EC) loggings, and five Ground-penetrating Radar (GPR) profiles. The geophysical measurements were acquired along landforms located in front of the caves of Hohlenstein-Stadel, in the Lone Valley, and Hohle Fels, in the Ach Valley.

The ERT method is a non-invasive geophysical technique for the characterization of the near-surface electrical resistivity distribution (e. g., Binley and Kemna 2005; Telford et al., 1990). For the ERT surveys, we used 28 to 50 electrodes along a straight profile, with a spacing of 1–1.3 m (the latter was used only for the tomography corresponding to line 5 in Fig. 5). For ERT data acquisition, a Lippmann 4point light 10W resistivity meter was used, and Schlumberger, Wenner, and Dipole-Dipole configurations were employed. The acquired geoelectrical measurements were evaluated by inversion with the Boundless Electrical Resistivity Tomography package (BERT2, Günther and Rücker 2017; Rücker 2010). Although characterized by a lower vertical resolution, Dipole-Dipole methods typically resolve better horizontal variations in electrical resistivity (Zhou and Dahlin 2003), thus allowing for the separation of the main lithological bodies detected in our survey areas. For this reason, we present exclusively the results we obtained with the Dipole-Dipole configuration.

EC-logging refers to the measurement of the vertical distribution of the subsurface electrical conductivity (Schulmeister et al., 2003) using the Direct Push technology (Leven et al., 2011). In the field, we acquired EC data with a vertical resolution of 15 mm using a Geoprobe® 6610 DT Direct Push unit in combination with a Geoprobe® SC-500 Soil Conductivity System (Wenner-array probe with electrode spacing of 20 mm).

GPRs are designed to transmit and receive high-frequency electromagnetic waves to and from the subsurface (Annan 2009). Based on results from previous GPR investigations carried in the same study region (Barbieri et al., 2018; Barbieri 2019), we conducted our survey with a GSSI TerraSIRch SIR System-3000 connected to a 200 MHz antenna and a survey wheel, recording 70 to 100 scans per meter. Data were processed with the software Reflex (for more info see SI1).

ERT, EC-logging and GPR data were topo-corrected based on elevation points measured with Differential-GPS (DGPS) and total station.

3. Results

3.1. Lone Valley

Here we present the results of an ERT survey conducted on a river terrace located along the North hillside opposite from the cave of Hohlenstein-Stadel (ERT survey 1 to 6 in Fig. 5). This feature was previously investigated with GPR, EC-logging, and coring (Barbieri et al., 2018; Barbieri 2019). The dataset we present in this study consists of six ERT measurements collected along six profiles.

3.1.1. ERT surveys

From 0.5 to 1 m below the ground surface we recovered resistivity values between 40 and 80 Ωm along the entire length of the six ERT profiles (A, in Fig. 6). Underneath this potential lithological unit, along the North flank of the slope, we detected values of apparent resistivities from 80 to 100 Ωm (B in Figs. 6 and 7). Down to 4 m of depth in the middle of the valley we measured resistivity values higher than 200 Ωm (C in Figs. 6 and 7). This potential lithological unit appears to cover

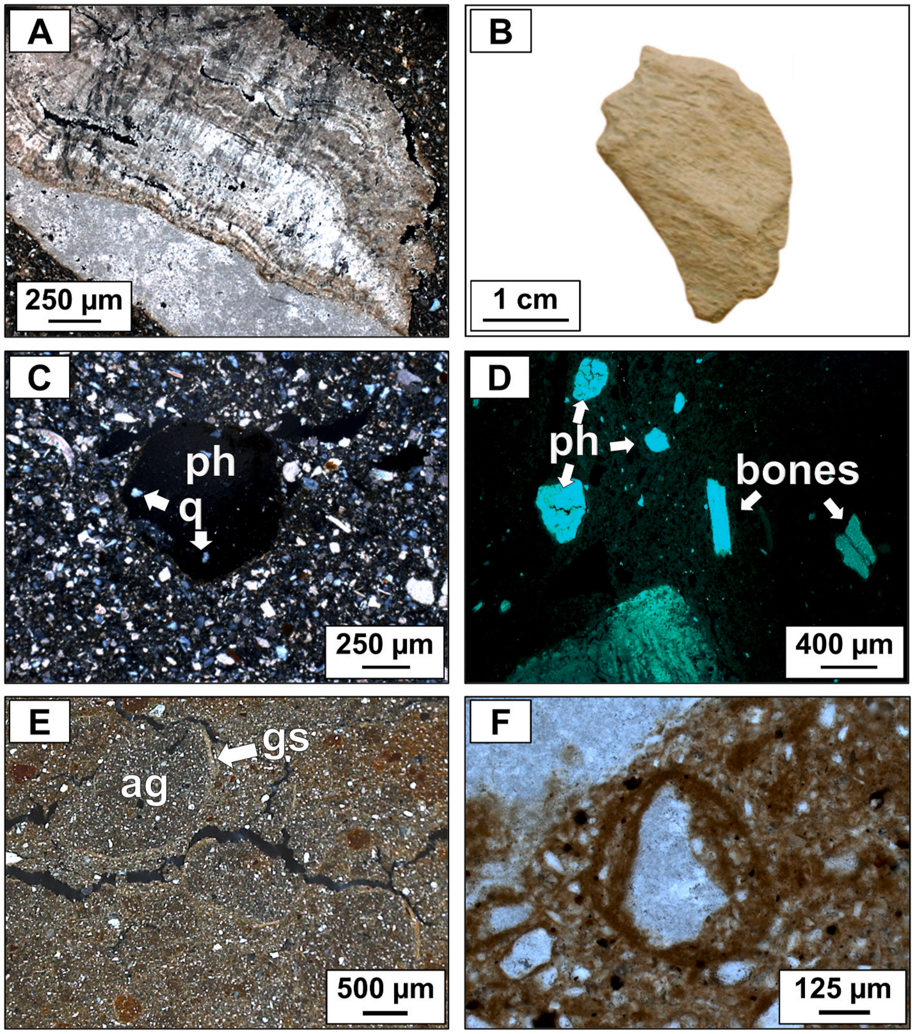

Fig. 4. Evidence of cave and landscape erosion from Ach and Lone ValleyLone Valleys. Speleothem (A) and bone fragment (B) from Hohle Fels, grains of phosphatized loess (C) and bones (D) from Bockstein, cryogenic features (E and F) from the hillside opposite Hohlenstein-Stadel.

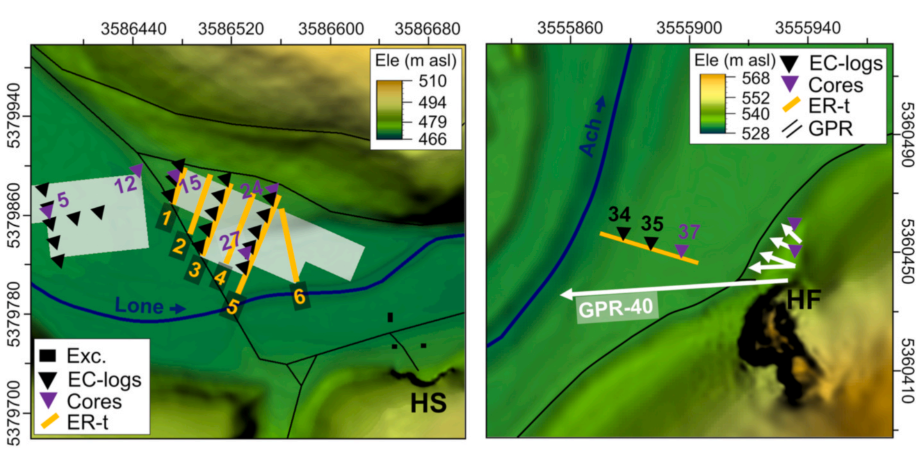

Fig. 5. Location of geophysical measurements. On the left, geophysical measurements in the Lone Valley opposite from Hohlenstein-Stadel (***HS***). Black rectangles downslope from *HS* show the location of the excavation led by Bolus et al. (1999). Black triangles, purple triangles, and white rectangles show respectively the location of EC-logs, cores and GPR measurements published in Barbieri et al., (2018) and Barbieri (2019). Orange lines show the location of ERT surveys presented in this study. **On the right**, geophysical measurements in the Ach Valley downslope from Hohle Fels (***HF***). Purple triangles show the location of cores published in Barbieri et al., (2018) and Barbieri (2019). Black triangles, orange lines and white lines show the location of EC-logs, ERT surveys and GPR profiles, respectively, presented in this study. Both maps are projected in the DHDN-Gauss-Krüger coordinate system (EPSG: 31467). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

sediments displaying resistivity between 100 and 130 Ωm (D in Fig. 7). The sediments accumulated in the center of the valley are not laterally continuous and appear incised by three depressions. The first one is localized underneath the north hillside, it appears at least 15 m wide (north-south), 100 m long (east-west) and 5–8 m deep (E in Figs. 6 and 7). We traced a second potential depression at the passage from the hillside to the river plain. It measures 20 m in width (north-south), at least 80 m in length (east-west) and 1.5 m in depth (F in Fig. 7). In the

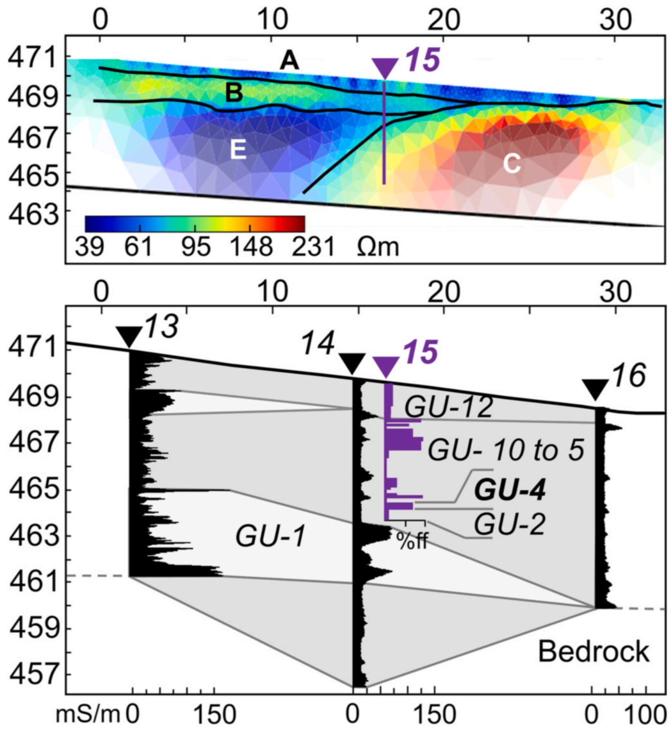

Fig. 6. Results from the Lone Valley, opposite from Hohlenstein-Stadel – part 1. Above, ERT survey 1, for the location of the measurement see Fig. 5. ***A***, ***B***, ***C***, ***E*** main potential lithological units distinguished in this tomography. ***15*** marks the location of core 15 (see also Fig. 5), **Below**, results from previous EC-logging and coring (based on Barbieri et al., 2018; Barbieri 2019). The lithology of core 15 is illustrated in purple as percentage of fine fraction (***%ff***) (Based on Barbieri 2019). The max percentage displayed is 95%. ***GU***s show the location of HS-GUs mentioned in the text. (HS-)***GU-4*** was radiocarbon dated to 29 Kcal BP (Barbieri et al., 2018; Barbieri 2019). In both graphs, *upper x axis* indicates distance from the start of the survey line, *y axis* shows elevation (m asl). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

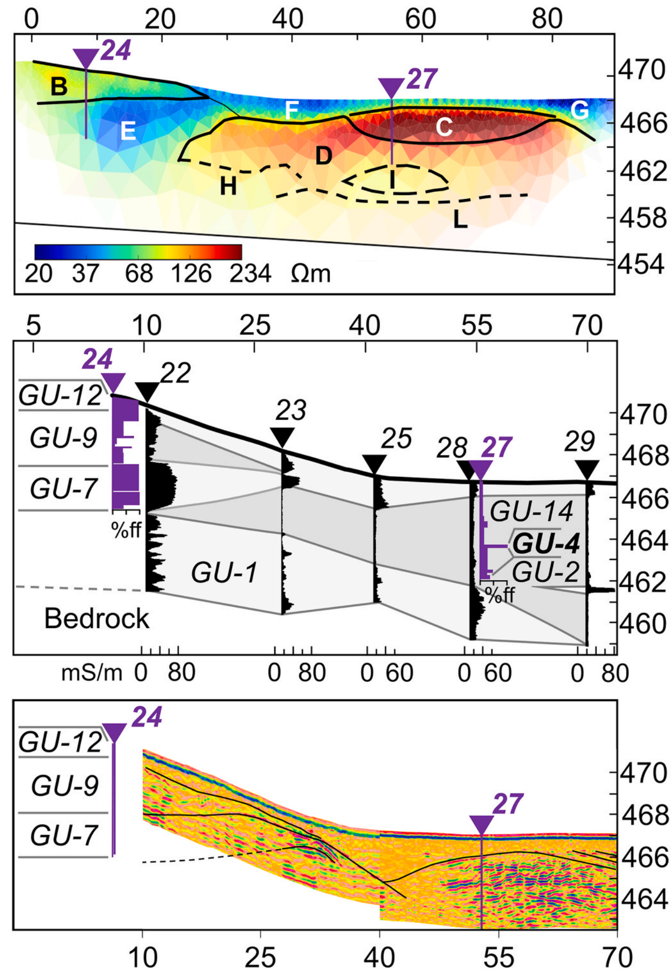

Fig. 7. Results from the Lone Valley, opposite from Hohlenstein-Stadel – part 2. Above, ERT survey 5, for the location of the measurement see Fig. 5. ***B, C, D, E, F, G, H, I, L*** are the main potential lithological units distinguished in this tomography. ***24*** and ***27*** mark the location of the respective cores (see also Fig. 5). **Middle**, results from previous EC-logging and coring (based on Barbieri et al., 2018; Barbieri 2019). The lithology of cores 24 and 27 is displayed in purple as percentage of fine fraction (***%ff***) (Based on Barbieri 2019). The max percentage displayed is 100%. ***GU***s show the location of HS-GUs mentioned in the text. (HS-)***GU-4*** was radiocarbon dated to 29 Kcal BP (Barbieri et al., 2018; Barbieri 2019), while the upper part of (HS)***GU-14*** exhibited fragments of pottery (Barbieri et al., 2018; Barbieri 2019). **Below**, result from previous GPR measurement acquired along the same line where ER, EC, and coring data have been acquired (based on Barbieri 2019). In all three graphs, *x axis* indicates distance from the start of the survey line, *y axis* shows elevation (m asl). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

last 10 m of our tomography profiles we detected a potential third depression, which appears at least 80 m long (east-west) and 2 m deep (G upper right detail of Fig. 7). All these features are filled with sediments exhibiting resistivity values mostly lower than 50 Ωm.

In the central part of the floodplain, below 5–6 m of depth, we detected potential deposits showing resistivity between 80 and 100 Ωm. Such values appear clustered in two zones located respectively 20–45 m (H in Fig. 7) and 50 to 70 m from the start of line (I in Fig. 7). Below 5 m of depth, in between these two zones and at the bottom of unit H we measured resistivity between 130 and 250 Ωm (L in Fig. 7).

3.1.2. Ach Valley

Our dataset from Hohle Fels consists of one ERT profile, two EC-loggings (EC-34, EC-35), and five GPR transects (Fig. 5).

We acquired ERT profile, EC-34, and EC-35 along a 30 m-long survey line, crossing the Ach Valley at the foothill of Hohle Fels (Fig. 5). From ER-1 we collected data down to 4 m of depth, while we stopped our EC-logging at 12 m below the ground surface, because of limitations in the drilling permission. EC-34 and EC-35 were previously published in Barbieri (2019). In this paper we present a more precise topo-correction of these data, based on new DGPS elevation points, which revealed a more exact geometry of the deposits buried in this portion of the Ach Valley.

Most of our GPR data were collected along the break-in-slope at the entrance to the cave of Hohle Fels, while GPR-40 was acquired from this landform down to the Ach River (Fig. 5). GPR-40 was previously published as topo-corrected raw data in Barbieri (2019, Fig. 5.8 p. 133), in this paper it is fully processed.

3.1.3. ERT surveys

Our ERT survey results show the occurrence of two main lithological units. In the uppermost meter of our tomography, up to 25 m from our first electrode, we obtained resistivity values between 150 and 500 Ωm (M in Fig. 8). Below these sediments, down to the bottom of the tomography, we detected resistivity between 20 and 50 Ωm (N in Fig. 8).

3.1.4. EC-logging

Down to 1 m below the modern soil, our logging measured conductivity mostly lower than 30 mS/m, with only rare peaks up to 80 mS/m (Barbieri 2019. O in Fig. 8, here on EC-O). Between 1 and 2.5 m below the ground surface we acquired values higher than 70 mS/m (Barbieri

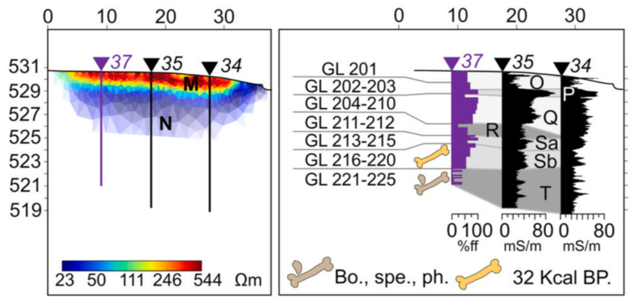

Fig. 8. ERT survey and EC-logging results from the Ach Valley, downslope from Hohle Fels. On the left, ERT survey data. **On the right**, EC-logs ***34*** and ***35*** (in black) collected along the same line as the ERT survey. In purple core ***37***, its lithology (as percentage of fine fraction, ***%ff***), and its geological layers (***GL***) mentioned in the text (based on Barbieri 2019). ***Bo., spe., ph.*** show the location of fragments of bones, speleothems, and phosphatized grains in core 37. In orange, the location of a bone fragmented dated to 32 Kcal BP (Barbieri et al., 2018; Barbieri 2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2019. P in Fig. 8, here on EC-P). Down to a max depth of 5 m in EC-35 and 6 m in EC-34, our logging measured values between 50 and 70 mS/m (Q in Fig. 8, here on EC-Q). Underneath these potential lithological units, we identified a drop in conductivity of 20 mS/m, which might correspond to a deposit measuring 1 m in thickness in EC-35, and 0.1 m in EC-34 (R in Fig. 8, here on EC-Q). At depths between 6 and 8 m in both EC-34 and EC-35 we detected a 0.2 m-thick deposit exhibiting ca. 20 mS/m, which separates two more conductive sediments displaying 40–50 mS/m (Sa and Sb in Fig. 8, here on EC-Sa and EC-Sb). Below ca. 8 m of depth our logging revealed sediments with a conductivity mostly lower than 20 mS/m (T in Fig. 8, here on EC-T). EC-Sa, EC-Sb, and EC-T share similar geometry, indeed all these potential lithological units seem to slope from EC-34 towards EC-log 35.

3.1.5. GPR

Along the floodplain, down to a maximum depth of 1.5 m, our GPR survey detected hyperbolas exhibiting velocities of 0.06–0.08 m/ns. GPR data from this portion of the river plain revealed the occurrence of reflectors delimiting two (or possibly three) distinct, stacked depressions, which appear 0.8 m–1.5 m deep and 10 m–50 m wide (North-South. U in Fig. 9, here on GPR-U). These depressions are cut by a ca. 2 m deep, 4 m wide trench, at the bottom of which we detected a hyperbola exhibiting velocity of 0.11 m/ns (likely corresponding to a gas line, Fig. 9). Below 2 m of depth, along the river plain, we encountered strong attenuation of the radar signal (V in Fig. 9, here on GPR-V). The

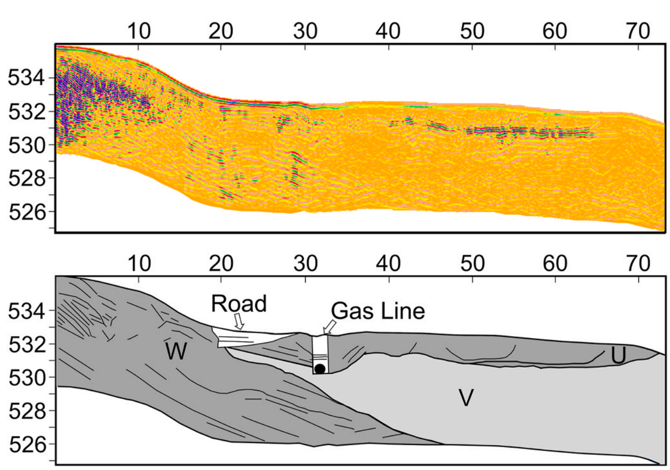

Fig. 9. GPR data from Hohle Fels, profile GPR-40. Above, processed GPR data. For the position of the measurement see Fig. 5. **Below**, data interpretation.

potential sedimentary structures we reported from the floodplain seem to rest on top of stratified deposits accumulated along the slope. These sediments display velocities of 0.08–0.09 m/ns and appear to dip mostly towards the center of the valley (W in Fig. 9, here on GPR-W). Closer to the cave entrance, GPR-W appears truncated by the modern topography, while at the foot of the slope it is cut by sub-horizontal reflectors, likely indicating the foundation of the asphalt road that stretches along the valley flank (*Road* in Fig. 9, see also Fig. 5).

4. Discussion

4.1. Fluvial dynamics and cave erosion

4.1.1. The Lone Valley

In the survey area opposite from Hohlenstein-Stadel below 8 m of depth we measured ER values between 130 and 250 Ωm (L in Fig. 7, from here on ER-L). This lithological unit displays depth and electrical resistivity compatible with limestone bedrock (Reynolds 1997, p. 422). Our interpretation is further supported by previous EC-logging, coring (Fig. 6, Barbieri et al., 2018; Barbieri 2019) and seismic measurements conducted across the Lone Valley (Schneidermeier 1999).

Above ER-L, between 20 and 40 m from the start of our ERT profiles we recorded resistivity between 80 and 100 Ωm (H in Fig. 6, from here on ER-H), which is comparable with silty clay deposits (Reynolds 1997, p. 422). Our previous EC data from below 5 m of depth detected a sequence composed of generally conductive sediments (50 mS/m) alternating with multiple, thin (ca. 0.3 m) resistive deposits (25 mS/m, Fig. 6. Barbieri 2019). Coring (core 5, Figs. 5 and 10) confirmed that this unit corresponds to silty clay sediments alternating with layers of gravel and cobbles (HS-GU1, Barbieri 2019). We argue that the thinner resistive beds within HS-GU1 could not be resolved by means of ERT due to limitations of this method (Reynolds 1997).

Based on the comparison between electrical resistivity data published in this paper and results from previous coring and EC-logging, we argue that ER-H/HS-GU1 was incised by erosional processes (Barbieri

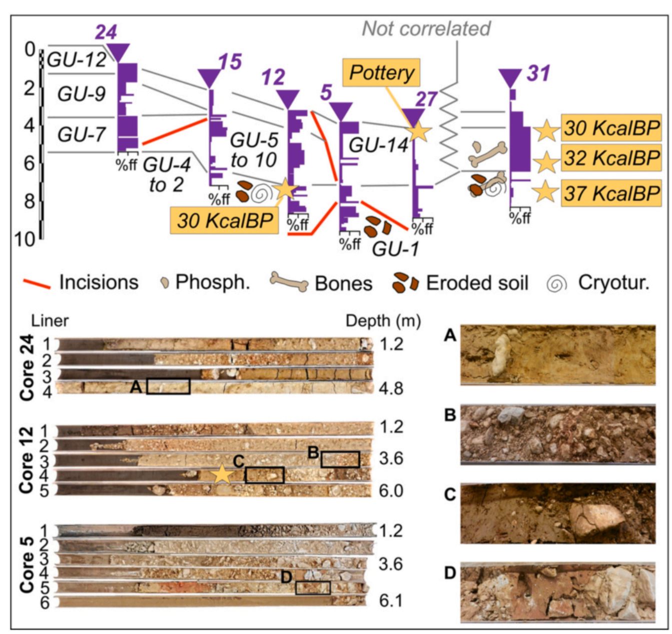

Fig. 10. Phases of river valley incision and cave erosion in the Lone Valley. A, detail from HS-GU7 in core 24; B, detail from HS-GU5 in core 12, D, detail of HS-GU4 in core 12, D, detail from HS-GU1 in core 5. Major incisions (in orange) are based on ERT surveys presented in this paper and EC-logging, GPR and coring published in Barbieri et al., (2018) and Barbieri (2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

et al., 2018; Barbieri, 2019). This incision is located 80 m to the north of the cave of Hohlenstein-Stadel, and it is 50 m wide and 5.5 m deep (Fig. 6). This landform was filled with conductive deposits (I in Fig. 6) alternating with more resistive sediments (D in Fig. 6, here on ER-D). This infilling likely corresponds to the HS-GU2 to HS-GU10 sediments (Fig. 6), which Barbieri (et al., 2018, 2019) described as gravel beds alternating with rare silty clay deposits of fluvial (HS-GU3, HS-GU6) and colluvial origin (the remaining units from HS-GU2 to HS-GU10. Details B and C in Fig. 10. Barbieri 2019). Within the HS-GU2 to HS-GU10 sequence, ^{14}C dating from HS-GU4 seems to indicate that the incision of ER-H/HS-GU1 took place before 30 Kcal BP (Fig. 10. Barbieri et al., 2018; Barbieri 2019). A few kilometers to the west from Hohlenstein-Stadel, downslope from Bockstein, deposits exhibiting chronology and lithology comparable to HS-GU2 to HS-GU4 show reworked soil material and sand sized fragments of bones likely coming from the cave sites situated on the higher hillslope (core 31 in Fig. 10. Barbieri et al., 2018; Barbieri 2019). This evidence shows that the erosion of cave deposits occurred after a major phase of valley incision (Fig. 10).

ER-D appears carved by one laterally continuous depression, which is located along the northern portion of the slope and was subsequently filled with sediments exhibiting resistivity lower than 50 Ωm (E in Fig. 6, here on ER-E). In agreement with our ERT data, previous EC-logging and coring (Barbieri et al., 2018; Barbieri 2019) suggested the occurrence of a potential paleo-channel running along the north flank of the Lone Valley (HS-GU7, Barbieri et al., 2018; Barbieri 2019. Fig. 7). The bottom of this paleo-channel corresponds to a 0.2 m thick resistive layer composed of coarse pebbles, which top the more conductive HS-GU1 deposits (Fig. 7). Our ERT surveys were ineffective in detecting this cobble layer, due to its low thickness. As such, the potential paleo-channel filled with ER-E appears deeper in the ERT than in the EC-logs. Data from previous coring show that ER-E corresponds to water-deposited loess alternating with rare gravel beds (HS-GU7 in Fig. 10, Barbieri et al., 2018; Barbieri 2019). In previous publications we argued that HS-GU7 marked a shift towards increasing loess depositions in the Lone Valley, possibly indicative of approaching LGM conditions (Barbieri et al., 2018; Barbieri 2019). At the entrance to the cave of Hohlenstein-Stadel, increasing loess sedimentation marked also the end of cave erosion around 16 Kcal BP (Barbieri et al., 2018; Barbieri 2019). Hence, we argue that the incision filled with ER-E/HS-GU7 might have occurred while cave erosion was still active at Hohlenstein-Stadel. ER-E was later covered with coarser sediments of colluvial origin (A and B corresponding to HS-GU12 in Fig. 6).

Our ERT data show that ER-D was possibly carved by one depression located in the center of the floodplain, measuring some 2.5 m in depth, 30 m in width (North-South), and at least 80 m in length (East-West). This potential incision was filled with sediment exhibiting resistivity higher than 200 Ωm (Fig. 7). Previous GPR and coring data from this area confirmed the occurrence of a potential river incision filled with dry, cross-bedded gravels (HS-GU14 in Fig. 7. Barbieri et al., 2018; Barbieri 2019). The deposition of these sediments possibly took place towards the end of the Pleistocene and the beginning of the Holocene, as suggested by the presence of sand-sized grains of pottery in the upper part of HS-GU14 (Fig. 10, Barbieri et al., 2018; Barbieri 2019). Subsequently, the deposits accumulated at the foot of the slope and in the southernmost portion of our survey area were incised and filled with conductive sediments (F and G in Fig. 7), which corresponds to silty clay deposits (Fig. 7, Barbieri 2019). During these incisions and aggradations, the Lone River progressively migrated from the north hillside towards the center of the valley, where it flows today (Barbieri et al., 2018; Barbieri 2019).

4.1.2. The Ach Valley

In the Ach Valley our EC-logging from below 8 m of depth detected sediments exhibiting ca. 20 mS/m alternating with rare, thinner beds displaying ca. 50 mS/m (EC-T in Fig. 8). Between 6 and 8 m of depth we identified slightly more conductive deposits, showing values mostly between 50 and 60 mS/m (EC-Sa and EC-Sb in Fig. 8). These sediments are covered with a lithological unit exhibiting conductivity of 40 mS/m (EC-R in Fig. 8). From core 37 we previously reported deposits showing depth and lithology comparable with EC-R (GL 211 and GL 212), EC-Sa (GL 213 to GL 215), EC-Sb (GL 216 to GL 220), and EC-T (GL 221 to GL 225. Fig. 8. Barbieri et al., 2018; Barbieri 2019). All these sediments appear gleyed and are composed of silty clay gravel beds alternating with occasionally graded bedded and cross-bedded layers of reworked, decalcified loess (Fig. 11. Barbieri 2019). In GL 220 to GL 225 we previously identified components likely eroding from the cave of Hohle Fels, such as grains of phosphatized loess, speleothems, and bones (Barbieri et al., 2018; Barbieri 2019). A bone fragment from GL 220 was radiocarbon dated to 32 Kcal BP (Fig. 10. Barbieri et al., 2018; Barbieri 2019), which falls in the Gravettian time period as published for the site of Hohle Fels (Taller and Conard 2016). The lower contacts of EC-R/GL 211–212, EC-Sa/GL 213–216, and EC-Sb/GL 217–225 appears to delimit three distinct, stacked depressions (Fig. 8). Given the presence of graded laminations in GL 211 to GL 219 and cross-bedding in GL 220 (Barbieri 2019) we hypothesize that these depressions might corresponds to former river beds of the Ach River. This hypothesis is confirmed by previous ER data from the Ach Valley (Dvorak 1975, for more information see SI1), which show that sediments exhibiting electrical properties comparable with EC-T/GL 221–225 fill a potential river incision measuring at least 7 m in depth and 80 m in width (α in Fig. 11). These data indicate that during the erosion of Gravettian-aged sediments the Ach flowed not more than 50 m to the north of the entrance to Hohle Fels.

The top of EC-R appears truncated and covered with more conductive sediments, corresponding to EC-Q (Fig. 8). Similar morphology and electrical properties were detected also by our GPR surveys (transition from GRP-W to GPR-V in Fig. 9) and previous ER measurements (passage from γ to δ in Fig. 11, Dvorak 1975). Based on these data, we argue that this contact was shaped by erosional processes. In core 37, at depths comparable with this unconformity, we previously reported the passage from GL 211 to GL 212 (Fig. 10, Barbieri et al., 2018; Barbieri 2019). Although clear to diffuse, this transition corresponds to an increase in oxidized, calcite rich, reworked loess, which likely reflects a shift

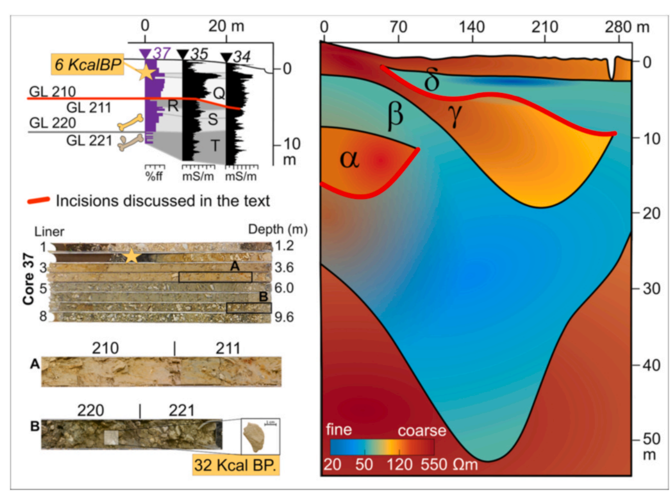

Fig. 11. Main phases of river valley incision and cave erosion in the Ach Valley. On the left, EC data presented in this text, data and photos from core 37 (modified from Barbieri 2019) showing the potential disconformity discussed in the text (**GL 201** to **GL 211**) and the location of the dated bone fragment eroding from Hohle Fels in **GL 220**. **On the right**, correlating our results with the interpretation of ER profile A (modified from Dvorak 1975. The location of these data is in Fig. 2, in SI1). We propose that **α** correlates with our EC-T/GL221-225, **β** with EC-S/GL211-213, **γ** with EC-R/GL211-212 and **δ** with EC-Q/GL204-210.

towards colder and drier climate comparable with the LGM (Barbieri et al., 2018; Barbieri 2019). It is possible that the truncation of EC-R/GPR-W/GL 211 triggered the removal from Hohle Fels of deposits dating between 32 Kcal BP and the LGM. However, the lack of materials potentially eroding from Hohle Fels in the sediments covering this unconformity (GL 204–210), would not support this hypothesis. Further and more intensive micromorphological investigation of these deposits is clearly needed.

Our EC results show that EC-Q is covered with highly conductive deposits (EC-P, 70 to 90 mS/m), which likely correspond to a peat-like sediment dating to 6 Kcal BP (GL 202–203, Fig. 11. Barbieri et al., 2018; Barbieri 2019). This peat was possibly eroded and covered with more resistive sediments (EC-O, ER-M, GPR-U, Fig. 8), which, based on previous coring, correspond to fluvial gravel, containing pottery and charcoal fragments dating to 300 cal BP (GL 201, Fig. 8. Barbieri et al., 2018; Barbieri 2019).

4.2. Human behavior, cave erosion and preservation of the Gravettian record in the lone and ach valleys

Data published in this paper, in agreement with previous studies (Barbieri et al., 2018; Barbieri 2019), show that Gravettian-aged materials (37-28 Kcal BP) eroded from caves of Ach and Lone valleys, after a major phase of river incision. Downcutting in the rivers of the southern Swabian Jura was activated by hydrological and geomorphological processes that started downstream in the Danube Valley (Eberle et al., 2010; Schellmann 2010), such as the Alpine glaciation (Preusser et al., 2010; Ellwanger et al., 2011), the subsidence of East European regions (Miklós and Neppe 2010; Necea et al., 2013) and drops in the Black Sea water level (Fairbanks 1989; Wingutha et al., 2000). Although related with these continental processes, river incision in Ach and Lone valleys was more directly controlled by regional changes in climate and hydrology. During transitions from colder to cooler or from cooler to colder climate, the combined effect of discontinuous permafrost (Clark 1988) and denser vegetation (Sauer et al., 2016) increased the amount of snowmelt water drained within river channels and decreased the rate of hillside erosion. These settings allowed the Ach and Lone rivers to carve their beds (Barbieri et al., 2018). During colder and drier periods (like the LGM), the landscape was de-vegetated (Sauer et al., 2016), and the snowpack was thicker, denser (Kuusisto 1984), and with lower albedo than during cooler and wetter times (Warren 1984). As result, melting periods were characterized by a sudden and intensive discharge of water (Kuusisto 1984), which saturated the sediments accumulated along the valley flanks and infiltrated down to the karst system. Inside caves, at least part of this water drained at the ground surface and flowed towards the dripline, following the gentle (≥6°) inclination of the local topography. This cyclic process carved rills and gullies inside numerous caves, such as Hohlenstein-Stadel (Fig. 3), Hohle Fels (Fig. 2), Bockstein-Schmiede (Wetzel and Bosinski 1969), Vogelherd (Riek 1934) and Sirgenstein (Schmidt 1912). Along the hillsides, mass-wasting processes moved cave and slope sediments towards the valley bottom, preventing further river incision (Barbieri et al., 2018). This process was probably more dramatic in the cold periods that occurred shortly after phases of downcutting, when the de-vegetated valley flanks were rapidly adjusting to the drop in base level. Since we expect that the rate of cave erosion depended on the intensity of slope erosion, we hypothesize that the removal of sediments and archaeological finds from caves was more intensive in the cold periods that followed phases of downcutting. This hypothesis is well supported by previous data, showing that materials eroding from caves and soils are abundant above valley incisions (Barbieri et al., 2018; Barbieri 2019).

We expect that the impact of downcutting on cave sedimentation was higher in the caves located closer to the valley bottom, like Hohle Fels (4 m above the Ach) and Holenstein-Stadel (7 m above the Lone plain). On the other hand, despite resting at similar elevations, these two sites exhibit very dissimilar Gravettian record. This observation is also valid when comparing other sites, with the caves from the Lone Valley systematically poorer in Gravettian materials (Barbieri 2019, see Table 1 in SI1). Therefore, we propose that other factors need to be taken into account in order to explain the regional pattern observed for the Swabian Gravettian, such as human behaviors and the exact timing of geomorphological processes.

4.2.1. Is the lack of materials and deposits dating to the Gravettian (35-30 Kcal BP) in the Lone Valley due to human behavior?

Aurignacian deposits inside Hohlenstein-Stadel are considerably poorer in anthropogenic materials than the sediments preserved inside Hohle Fels (See section 4 of the SI1). This dissimilarity is probably related with a difference in the use of the cave (Kitagawa 2019), with Hohlenstein-Stadel likely serving as site for religious practice (Kind et al., 2014). If such use lasted during the middle Upper Paleolithic, probably little evidence of human occupation accumulated inside this site prior to cave erosion. If the whole Lone Valley was depopulated or less intensively inhabited, even less material would have been deposited inside Hohlenstein-Stadel and the other caves of this part of the Swabian Jura. Such little evidence of human presence might have been extensively removed during the erosive phase. On the other hand, rich Gravettian assemblages might have been preserved in the Ach Valley simply because more materials were accumulated by humans prior to erosion. However, while changes or dissimilarities in settlement dynamics may explain the lack of Gravettian-aged materials in the caves of the Lone Valley they do not explain the lack of Gravettian-aged sediments. Therefore, other geogenic processes must be considered in order to explain this gap in the archaeological record of the region.

4.2.2. Did cave erosion move with a time lag across the study region?

The geochronology of cave erosion in the Swabian Jura is based on four radiocarbon dates, namely one bone fragment (32 Kcal BP) from in front of Hohle Fels, two samples of mixed shells (32 and 28 Kcal BP) and one of total organic carbon (37 Kcal BP) downhill from Bockstein (Barbieri et al., 2018; Barbieri 2019). The mixed shell samples show good preservation of aragonite but are likely coming from different snails. Similarly, we cannot exclude that the total organic carbon originated from multiple sources, exhibiting different chronology. For this reason, we should regard these three dates as averages. All these specimens (including the bone from Hohle Fels) are from colluvial layers showing fragments of speleothems and grains of phosphate eroding from the caves, therefore they should be considered as a terminus *post quem* for the time of erosion (Barbieri et al., 2018). Despite these issues, we previously argued that these four radiocarbon dates allow us to correlate the time of cave erosion (37-28 Kcal BP) with the period during which Gravettian humans inhabited the Ach Valley (Barbieri et al., 2018; Barbieri 2019). However, given their uncertainties, these ^{14}C ages should not be used to test whether cave erosion did or did not occur at different times throughout the region.

In stark contrast with the limited dating from our cores, the Pleistocene deposits preserved in the Swabian Jura yielded up to 400 radiocarbon ages. Such a rich database has been used to support hypotheses regarding human migrations, such as the depopulation of the region during the LGM (Jochim et al., 1999; Terberger and Street 2002; Kind 2003; Terberger 2003; Küßner and Terberger 2006; Maier 2015), and the subsequent short-lived Magdalenian repopulation (Taller et al. 2014, 2019; Taller 2015). These paleodemographic interpretations assume that the absence of organic materials dating to certain time intervals indicates periods during which humans did not use (or use less intensively) the cave sites. Based on our geoarchaeological data, this assumption is questionable. We have shown that between the Late Pleniglacial and Late Glacial, erosional processes formed gullies and disconformities within the caves and moved sediments and materials out from the caves (Miller 2015; Barbieri 2019; Barbieri and Miller 2019b; Barbieri et al., 2018). Secondly, more secure indicators of human absence, such as sterile sediments dating to the Late Pleniglacial, LGM and early Holocene are absent within the sites of the Swabian Jura. These observations suggest that the lack of materials dating to these time periods should be interpreted primarily as the result of intensive erosional processes.

Of the over 400 dates available from the Swabian caves we excluded all non-AMS dates, samples pretreated with ultrafiltration (since they were only a handful, Higham et al., 2012), determinations performed on mixed samples, and contaminated specimens. This selection reduces the dataset to 251 ^{14}C dates, which are plotted in Fig. 12 (for more information see SI 2). This dataset shows that date density drops to ≤3 ages/1Kyear and gaps lasting longer than 1 millennial are suddenly more frequent (ca. +400%) between 28 and 16 Kcal BP in the Ach Valley and between 36 and 18 Kcal BP in the Lone Valley. We interpret these gaps and their dissimilar timing as evidence that environmental conditions favoring cave erosion (depicted in orange in Fig. 12) and cave sedimentation (depicted in blue in Fig. 12) moved westwards through the Swabian Jura with a time lag of a few millennials.

Twelve ages from the Lone and five from the Ach Valley fall in the period dominated by more intensive cave erosion (Fig. 12, Table 2 in SI 2). These dates show that, despite prevailing on cave sedimentation, the removal of sediments and materials from the caves of this region was not a continuous process. This evidence correlates with the multiple phases of landscape erosion reported from this region (Barbieri et al., 2018; Barbieri 2019, and in this paper). Furthermore, these specimens come from mixed Middle and Upper Paleolithic assemblages unrevealed during excavations conducted with up to date documentation techniques, showing that in Swabia post-depositional processes caused both removal and mixing of cave deposits. Lastly, multiple specimens dating to the time of more intensive erosion have been likely modified by humans (see Table 2 in SI 2). As such, it remains to be proven whether and for how long the region was abandoned or less intensively populated at the end of the Pleniglacial and during the LGM.

The apparent westward shift in the timing of cave erosion in southern Germany follows similar patterns seen in other geochronological data from the region. The oldest Danube terrace exhibiting a reliable chronology dates to the Late Glacial and it is also known as *Niederterrasse 3* (Schielein et al., 2011; Schellmann 2010). This landform was marginally incised and filled with a sequence of peats and sands (Schielein et al., 2011; Schellmann 2010). Radiocarbon determinations performed on the lowermost peat yielded ages of 14 Kcal BP from the village Atting (near Regensburg, ***2*** in Fig. 1. Schellmann 2010), and of 11.5 Kcal BP from the confluence with the Lech River (north from Augsburg, ***1*** in Fig. 1, Schielein et al., 2011). These data show that the formation of the *Niederterrasse 3* moved westwards through the Danube Valley, covering a distance of 140 Km over a period of 3′500 years. A similar process, with a shorter time lag (1700 years), occurred also during the formation of the earliest Holocene terrace (Schellmann 2010; Schielein et al., 2011). The westwards movement of terrace formation during the Late Glacial and early Holocene appears confirmed by data from further downstream in the Danube catchment (the area between Straubing and Niederwinkling. Heine 1999; Münzberger 2005). Although dating is too sparse and imprecise to reconstruct the timing of terrace formation during the Pleniglacial and LGM (Münzberger 2005; Klasen 2008; Schellmann 2010; Geβlein and Schellmann 2011; Schielein et al., 2015), we expect that landscape changes moved westwards through the Danube Valley also in earlier times of the Pleistocene.

To sum up, based on published data we hypothesize that between the late Pleniglacial and early Late Glacial river incisions moved upstream throughout the Danube Valley, downcutting the Lone Valley few millennials earlier than the Ach. Subsequently, hillside erosion and intensive cave erosion began and terminated earlier in the Lone Valley. As result of this time lag, Gravettian-aged sediments were nearly entirely removed while early Magdalenian deposits preserved better in this part of the Swabian Jura. Further research is needed to confirm this hypothesis.

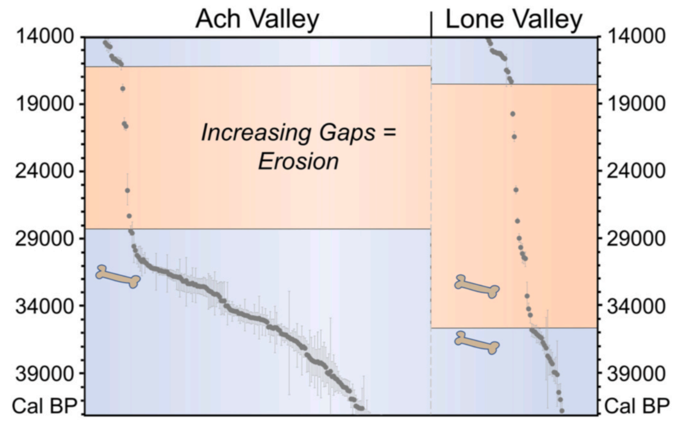

Fig. 12. AMS radiocarbon ages dating to the Upper Paleolithic (42-14 Kcal BP) from Ach and Lone valleys. This figure is based on data from Hahn (1995), Orschiedt (1996), Housley et al., (1997), Richter et al., (2000), Conard (2003), 2009, Conard et al., (2003), 2004, 2017, 2018, Conard and Bolus (2003), 2008, Conard and Moreau (2004), Bolus and Conard (2006), Hofreiter et al., (2007), Münzel and Athen, 2007, 2008, 2011, Immel et al., (2015), Yates et al., (2017), Hess (2019), Hornauer-Jahnke (2019b), Kind (2019c) (more info in SI2). Dots depict the mean value, while bars show the range of each date at 95.4% of probability (from OxCal 4.4). The bone symbols show the approximate chronology of sediments and bones eroding from the cave sites of Hohle Fels (Ach Valley) and Bockstein (Lone Valley).

5. Conclusions

Is the dissimilar Gravettian record (35-30 Kcal BP) preserved in the Swabian Jura resulting from a more intensive human presence in the Ach Valley? Although it is impossible to rule out completely this hypothesis, we argue that the paucity of Gravettian materials from the Lone Valley cannot be explained as resulting primarily from a phase of human depopulation or a preference for settling in one valley over another. In fact, the lack of sterile cave sediments dating to the Gravettian time period and the occurrence of Gravettian-aged materials redeposited downslope from Bockstein (Barbieri et al., 2018; Barbieri 2019) are convincing indicators of cave erosion. Similar processes occurred also in the Ach Valley, where bones, speleothems and phosphatized sediments eroded from the Gravettian deposits of Hohle Fels (Barbieri et al., 2018; Barbieri 2019). The most likely reason why the Gravettian record is preserved in one valley and nearly absent in the other is because erosional processes did not occur at the same time in the Swabian Jura. Based on radiocarbon data from the cave sites, we argue that erosion began during the Gravettian time period (35-30 Kcal BP) in the Lone Valley, while it probably commenced after the Gravettian time period in the Ach Valley. After the LGM, sediments and materials began to accumulate inside the caves of the Lone valley ca. 2 millennia earlier than in the caves of the Ach Valley. These recurrent delays suggest that conditions favoring accumulation and removal of cave sediments moved westwards through the Swabian Jura over a time span of few millennials. This hypothesis agrees with published geochronological data (Heine 1999; Münzberger 2005; Schellmann 2010; Schielein et al., 2011), which show that the formation of Pleistocene and Holocene terraces moved westwards through the Danube catchment.

Although more investigations are needed to further support this hypothesis, our study showed that the current knowledge of the Late Pleistocene humans that inhabited the Swabian Jura (and possibly the whole South Germany) results from a complex interaction between human behavior, erosion of archaeological deposits, and landscape changes.

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jas.2021.105335.

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