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Lithic assemblages from the Middle Paleolithic of Geißenklösterle Cave provide insights on Neanderthal behavior in the Swabian Jura

Steinartefaktinventare aus dem Mittelpaläolithikum des Geißenklösterle, Deutschland: Neue Erkenntnisse zum Verhalten der Neandertaler auf der Schwäbischen Alb

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Abstract - The Swabian Jura has long played a crucial role in key debates about the European Paleolithic. One of the best-known sites, Geißenklösterle Cave in the Ach Valley, has yielded a stratigraphic sequence including both Middle and Upper Paleolithic find horizons separated by a largely geogenic horizon. Here we present combined techno-economic and attribute analyses of the lithic artifacts from Middle Paleolithic horizons AH IV-VIII dating between ~90-45 ka BP. The lithic analyses demonstrate that Neanderthals mainly used the Levallois concept to knap locally available Jurassic cherts and produce small blanks and tools. Other raw materials occur as isolated artifacts. Apart from various modalities of Levallois technology, knappers employed Kostenki, bipolar and platform methods. Scrapers and splintered pieces are the most frequent tools, whereas notches, denticulates and bifacial implements including bifacially backed knives (*Keilmesser*) and leaf points (*Blattspitzen*) are absent. Low densities of archaeological finds and the export of selected blanks and tools indicate repeated short-term occupations of the site in a settlement system characterized by high mobility. Although minor diachronic variation occurs, assemblages IV-VIII show a distinct signature that can be attributed to the same general technological and techno-economic system. Regional comparisons suggest that the Middle Paleolithic assemblages from Geißenklösterle correspond to the Swabian Mousterian, which is defined by the use of local raw materials, frequent Levallois reduction sequences, multiple scraper forms, and an almost complete absence of bifacial technology including *Keilmesser* and *Blattspitzen*. The upper Middle Paleolithic assemblages dating to ~50-45 ka BP provide new insights into the behavior and demography of late Neanderthals prior to the arrival of anatomically modern humans. Overall, the archaeology of Geißenklösterle illustrates a sharp break in lithic technology, organic artifacts, subsistence strategies, site use and population dynamics between Neanderthals and *Homo sapiens* in southwestern Germany.

***Zusammenfassung -** Seit Beginn des 20. Jahrhunderts spielt die Schwäbische Alb eine zentrale Rolle für die Erforschung des Mittel- und Jungpaläolithikums in Europa. Das Geißenklösterle im Achtal stellt eine der wichtigsten Fundstellen dieser Region dar. Vor allem durch die Grabungen von J. Hahn von 1974-1991 bekannt, lieferte die Höhle eine lange und bedeutende archäologische Abfolge des Mittel- und Jungpaläolithikums, welche voneinander durch einen fundarmen Horizont getrennt sind. Der Fokus der Forschung auf die jungpaläolithischen Funde des Geißenklösterle führte dazu, dass eine detaillierte Beschreibung der Steinartefakte aus dem Mittelpaläolithikum bisher nicht vorgenommen wurde. Hier stellen wir die Auswertung von fünf Steinartefaktinventaren aus dem Mittepaläolithikum (AH IV-VIII) vor, welche auf ~90-45 ka BP datiert sind. Diese Inventare stammen hauptsächlich aus den Neugrabungen am Geißenklösterle durch N. J. Conard in den Jahren 2001 und 2002, die zum ersten Male die mittelpaläolithischen Schichten in größerem Umfang erfassten. Die Analyse der Steinartefaktinventare erfolgte anhand eines kombinierten Ansatzes von Attributanalyse sowie der Auswertung von Abbausequenzen und techno-ökonomischen Aspekten. Unsere Forschungsziele betrafen insbesondere die Charakterisierung der Neandertaler-Technologie auf synchroner und diachroner Ebene, die Einbettung der Inventare in das Mittelpaläolithikum der Schwäbischen Alb und Zentraleuropas, sowie Aussagen hinsichtlich Siedlungsmustern und Demographie. Die lithischen Inventare des Geißenklösterle sind relativ klein (n = 200; >20 mm), allerdings mit einer Vielzahl an Stücken <20 mm (n = 704) und häufigem Auftreten von Frostbeschädigungen. Die Neandertaler nutzten vorwiegend den lokal verfügbaren Jurahornstein, um kleine Abschläge und Werkzeuge mithilfe unterschiedlicher Abbaumethoden herzustellen, wobei Levallois den Hauptteil ausmacht. Andere Rohmaterialien wie Bohnerzhornstein, Muschelkalkhornstein, Radiolarit und Quarzit treten nur als isolierte Artefakte auf. Außer unterschiedlichen Varianten des Levallois-Konzepts konnte der Abbau von Kostenki, bipolaren und Plattform-Kernen nachvollzogen werden. Die Werkzeuginventare sind durch*

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häufige Schaberformen und seltenere ausgesplitterte Stücke gekennzeichnet, wohingegen gekerbte und gezähnte Stücke sowie bifazielle Werkzeuge (unter anderem Keilmesser oder Blattspitzen) vollständig fehlen. Die durchweg geringe Dichte an archäologischen Funden innerhalb des Mittelpaläolithikums, das Fehlen an Befunden und klaren Fundhorizonten, sowie der Export von ausgewählten Grundformen und Werkzeugen zeigt wiederholte kurzzeitige Belegungen der Fundstelle innerhalb eines Siedlungssystems mit hoher Mobilität an, vermutlich durch kleine Gruppen. Obwohl das Mittelpaläolithikum des Geißenklösterle geringfügige diachrone Veränderungen aufweist, zeigen Inventare IV-VIII jedoch insgesamt konsistente Signaturen, welche einem gemeinsamen techno-typologischen und techno-ökonomischen System zugeordnet werden können. Regionale Vergleiche belegen, dass die untersuchten Inventare mit dem Schwäbischen Moustérien übereinstimmen, welches durch die hauptsächliche Nutzung lokalen Rohmaterials, den häufigen Abbau durch das Levallois-Konzept, vielfältige Schaberformen und eine fast vollständige Abwesenheit von Keilmessern und Blattspitzen gekennzeichnet ist. Da die obersten Schichten des Mittelpaläolithikums auf ~50-45 ka datiert sind, geben unsere Befunde neue Einblicke in das Verhalten und die Demographie später Neandertaler, die in Südwestdeutschland direkt vor der Ankunft anatomisch moderner Menschen lebten. Zusammenfassend zeigt die archäologische Abfolge des Geißenklösterle einen scharfen Bruch in der lithischen Technologie, organischen Artefakten, Subsistenzstrategien, Fundplatznutzung und vermutlich Bevölkerungsdichte zwischen Neandertalern und Homo sapiens.

Keywords - Lithic Technology, Swabian Mousterian, Neanderthal mobility, Raw material economy, Levallois method, Settlement dynamics
Steinartefakttechnologie, Schwäbisches Moustérien, Mobilität der Neandertaler, Rohmaterialnutzung, Levallois-Methode, Siedlungsmuster

Introduction

Since the 1860s generations of archaeologists have conducted Paleolithic research in the Swabian Jura with the majority of excavations focusing on the caves of the Ach and Lone valleys (Fraas 1867; Schmidt 1910, 1912; Riek 1934; Müller-Beck 1983; Wagner 1983; Hahn 1988; Conard et al. 2015) (Fig. 1). These sites have provided important archaeological sequences that span the Middle and Upper Paleolithic (MP; UP). Most recent work has focused on the UP sequences and particularly the Aurignacian find horizons from

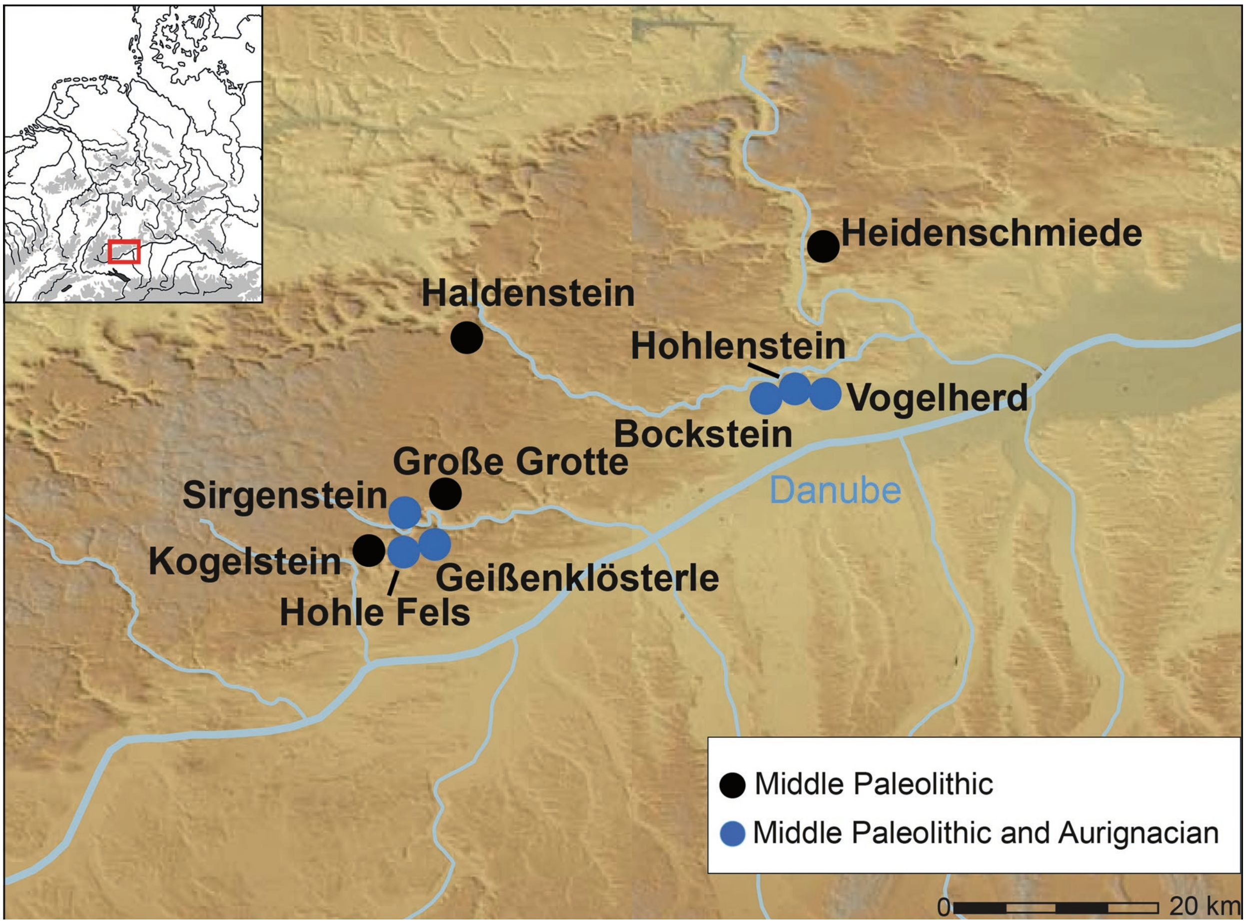

Fig. 1. Map of Geißenklösterle and other MP sites from the Swabian Jura mentioned in the text.

Abb. 1. *Geographische Karte zur Lage des Geißenklösterle und weiterer im Text benannter MP-Fundstellen auf der Schwäbischen Alb.*

the region. The early Aurignacian of the Swabian Jura reflects the first wave of expansion by modern humans into Central Europe (Conard & Bolus 2003, 2006, 2015; Conard et al. 2003a, 2003b; Higham et al. 2012), and has yielded early examples of figurative art, musical instruments and mythical imagery (Hahn 1986; Hahn & Münzel 1995; Conard 2003, 2007, 2009; Conard et al. 2009; Kind et al. 2014; Conard & Kind 2019) alongside a wide array of personal ornaments and numerous examples of innovations among the lithic and organic artifacts (Hahn 1988; Conard & Bolus 2003, 2006; Wolf 2014).

This paper presents the MP assemblages from Geißenklösterle Cave (GK) in the Ach Valley of the Swabian Jura. The artifacts analyzed here originate from J. Hahn's excavations in the 1980s and early 1990s and from N. J. Conard's excavation of GK in 2001 and 2002. Hahn published his key findings on the MP artifacts from the site in his important monograph from 1988 (Hahn 1988), and we have recently published a second monograph on GK that provides many new results focusing on subsistence, dating and environmental studies (Conard et al. 2019). Understandably, Hahn dedicated most of his monograph and publications on GK to the exceptional UP sequence. Due to his outstanding work and rigorous publications, GK is internationally known for its key Aurignacian sequence with two main find complexes of archaeological horizons (AHs) II and III. Subsequent work has done much to inform the scientific community about the important Gravettian horizons from the site (Conard & Moreau 2004; Moreau 2009).

In this paper we present a technological, typological and techno-economic study of the five MP horizons of the site. Our main goals were to document the operational sequences, including methods of core reduction, knapping techniques, and tool production. These studies aimed at identifying diachronic and synchronic variability within the GK sequence. We consider the cultural and chronostratigraphic sequence and how it fits with what we know about the MP of the Swabian Jura and Central Europe. Ultimately, this work helps us to refine our understanding of the technology, lifeways and demography of late Neanderthals living in southwestern Germany prior to the arrival of anatomically modern humans. One advantage of having waited to publish the details of the MP lithic assemblages from GK is that M. Richard has published new ESR dates from the site (Richard 2015; Richard et al. 2019), which together with earlier radiocarbon, ESR and luminescence dates makes the MP find horizons from GK the best dated ones from the Swabian Jura.

Background on the Middle Paleolithic in the Swabian Jura

In recent decades, studies of the MP in the Swabian Jura have received less scholarly attention compared to the well-known UP. This being said, MP occupations are known from numerous sites in the region (Fig. 1). They include Bockstein (Bocksteinloch, Bocksteinschmiede, Bockstein-Törle), Hohlenstein (Bärenhöhle and Stadel), Vogelherd and Haldenstein in the Lone Valley, as well as GK, Hohle Fels, Sirgenstein, and Große Grotte in the Ach Valley, and Kogelstein located in the adjacent Schmiech Valley. Less well-known sites include Heidenschmiede, Irpfelhöhle, Göpfelsteinhöhle and Schafstall II, and rare open-air sites such as Börslingen, Wippingen, Wittlingen and Winterhalde (e.g. Burkert et al. 1992; Fisher et al. 2008; Conard et al. 2012; Çep 2013; Floss & Schürch 2015; Floss et al. 2017). Previous work has generally focused on the question of Neanderthal technology and climatic adaptations in Central Europe during the Late Pleistocene. There has been an emphasis on examining the MP to UP transition, connected to questions about the arrival of the first modern humans to Europe and the subsequent extinction and replacement of Neanderthals.

One of the key findings of previous research is the consistent documentation of an occupational hiatus between MP and UP find horizons at several sites, including GK, Hohle Fels, Sirgenstein and Vogelherd (Schmidt 1912; Riek 1934; Hahn 1988; Conard 2005; Conard et al. 2006; Bolus 2011). Assuming, as seems likely, that Neanderthals always made the MP assemblages and modern human always produced the Aurignacian assemblages, the find horizons left by Neanderthals and modern humans are separated by largely geogenic horizons that are either sterile or very poor in archaeological finds. These observations support the 'population vacuum' hypotheses that modern humans migrated via the Danube Corridor into the Swabian Jura when few if any Neanderthals occupied the region. Initially, we assumed that this depopulation may have been caused by a cold and arid climatic phase, most likely the terrestrial equivalent of the Heinrich 4 event ca. 40 ka (Conard 2003; Conard et al. 2003a; Conard & Bolus 2006). Subsequent dating and environmental studies, however, have shown that modern humans arrived in the region between 43 and 42 ka calBP in a climatic phase that was neither remarkably cold nor dry (Higham et al. 2012; Miller 2015; Rhodes et al. 2018; Goldberg et al. 2019). These stratigraphic arguments for a sharp break in the settlement history of the Swabian Jura are consistent with a major shift in lithic technology, organic material culture, subsistence behavior and site use that suggests that little or no direct contact between Neanderthals and modern humans occurred in this region (Conard et al. 2012).

Previous archaeological research shows that the MP of the Swabian Jura is characterized by variable but often low levels of occupation intensity by Neanderthals. Most sites have yielded small MP lithic assemblages, although exceptions such as the rich and high-density find horizons of Bocksteinschmiede are also known in the region. In general, in both the Ach and Lone valleys, find densities are far lower in the MP than the Aurignacian find horizons at the same sites (Conard et al. 2006, 2012; Conard 2011; Bolus 2015).

Mammalian faunal assemblages from the MP cave sites are frequently dominated by cave bear, medium-sized carnivores and small ruminants, which normally reflect natural death assemblages. The anthropogenic faunas are often rich in remains of horse, reindeer and ibex, depending on the geographic position of the site (Münzel & Conard 2004; Krönneck et al. 2004; Niven 2006; Conard et al. 2012). MP organic tools are only represented by a few potential bone points and more numerous retouchers from Vogelherd, Große Grotte, Sirgenstein and Schafstall (Conard et al. 2006; Bolus 2015; Toniato et al 2018). Unambiguous features are rare in the MP deposits of the Swabian Jura, but notable exceptions come in the form of a fireplace at Sirgenstein VII/VIII (Schmidt 1912), and concentrations of burnt bone at several sites including Bocksteinschmiede, Große Grotte and perhaps Hohlenstein-Stadel (e.g. Wetzel & Bosinski 1969; Wagner 1983; Beck 1999).

Whereas the MP lithic technology and cultural stratigraphy of the region is generally well-known, there have been few more synthetic studies and a lack of assemblages with absolute chronometric dates deriving from excavations with modern field standards. Most of the lithic assemblages in the region are dominated by locally available raw materials (see below). The assemblages often contain highly reduced Levallois cores and diverse debitage products. Tools of these assemblages are characterized by various scraper forms, whereas bifacial implements are rare or absent. The tools generally reflect a low degree of standardization. These assemblages have been referred to as the Swabian Mousterian (Schmidt 1912; Riek 1934; Wagner 1983; Beck 1999; Böttcher et al. 2000; Conard et al. 2012; Bolus 2015). In contrast, assemblages with high proportions of bifacially backed knives (*Keilmesser*) and other bifacial forms are usually classified as belonging to the *Keilmessergruppe* (Micoquian or Pradnikian) (Richter 1997, 2016; Conard & Fischer 2000; Jöris 2003; Bolus 2015), with the richest assemblages coming from Bockstein and Heidenschmiede (Peters 1931; Wetzel & Bosinski 1969; Çep 2014; Çep & Krönneck 2015). The latest MP is characterized by the leaf points of the *Blattspitzengruppe*, well-known from sites such as Haldenstein (Riek 1938; Conard & Fischer 2000; Bolus 2004a, 2011, 2015; Richter 2016).

For all of these technocomplexes, absolute dating and chrono-cultural correlations have proven to be difficult. Among other problems, this is due to the limits of radiocarbon dating and the lack of recent fieldwork that could apply state-of-the art dating methods such as OSL, TL or ESR (see Conard & Bolus 2003, 2008; Higham et al. 2012). While most MP horizons in the Swabian Jura remain poorly dated (Bolus 2011, 2015), the great majority of currently known assemblages likely date to the Early and Middle Würmian (MIS 5d-MIS 3; Conard & Bolus 2008). The preceding Eemian Interglacial (MIS 5e) might be represented by the small assemblage from layer IX of Vogelherd (Riek 1934; Niven 2006) and the MP finds from the lower travertine of Stuttgart-Untertürkheim (Wenzel 2007).

Most of the well-known MP assemblages from the Swabian Jura were excavated between the 1930s and 1960s. While the archeologists leading these excavations adhered to high standards for their time, the fieldwork, of course, lacked important elements such as 3D piece-plotting, modern geoarchaeological analyses and the application of radiometric dating. Moving beyond the well-known excavations in the Swabian caves, numerous open-air sites have yielded MP assemblages, but almost all of these assemblages originate from undated surface collections (e.g. Burkert et al 1992; Floss and Schürch 2015). Only rarely have stratified MP finds been recovered, and only the late Middle Pleistocene site of Bollschweil in the Black Forest has been radiometrically dated (Rink et al. 2002). In order to move research on the MP of the Swabian Jura and Germany forward, it is of utmost importance to analyze well-dated assemblages from excavations conducted in accordance with modern field methods. Absolute dates are also crucial for defining the key features and temporal variability of technocomplexes such as the Swabian Mousterian. The MP assemblages from GK in the Ach Valley reported upon here, meet these conditions. Today, GK, Hohle Fels and Kogelstein remain the only three stratified MP sequences in the Swabian Jura deriving from modern fieldwork and associated with absolute dates, although Kogelstein has yielded only infinite ^{14}C ages (Böttcher et al. 2000). The excavations at GK and Hohle Fels with their excellent recovery and abundant contextual information provide the most detailed evidence for site-use and Neanderthal technological adaptations in the Swabian Jura.

The site of Geißenklösterle

The site of GK is situated in the Achtal – a former valley of the Danube – located 60 m above the valley floor at ~550 m a.s.l. (Fig. 2). The cave is part of a karst system within the Upper Jurassic limestone of the south-eastern region of the Swabian Jura (Baden-Württemberg). GK is one of the key Paleolithic sites in Europe, documenting human occupations during the Mesolithic, UP (Magdalenian, Gravettian, Aurignacian) and MP.

Discovered as an archaeological site by R. Blumentritt in 1957, excavations at GK started with the opening of test trenches in 1963 (G. Riek) and 1973 (E. Wagner) and were continued by J. Hahn (University of Tübingen) in 14 field seasons from 1974 until 1991 (Hahn 1988). The systematic field work by Hahn uncovered deposits of over 4 m in thickness that were excavated in an area of approximately 45 m^2 for the UP

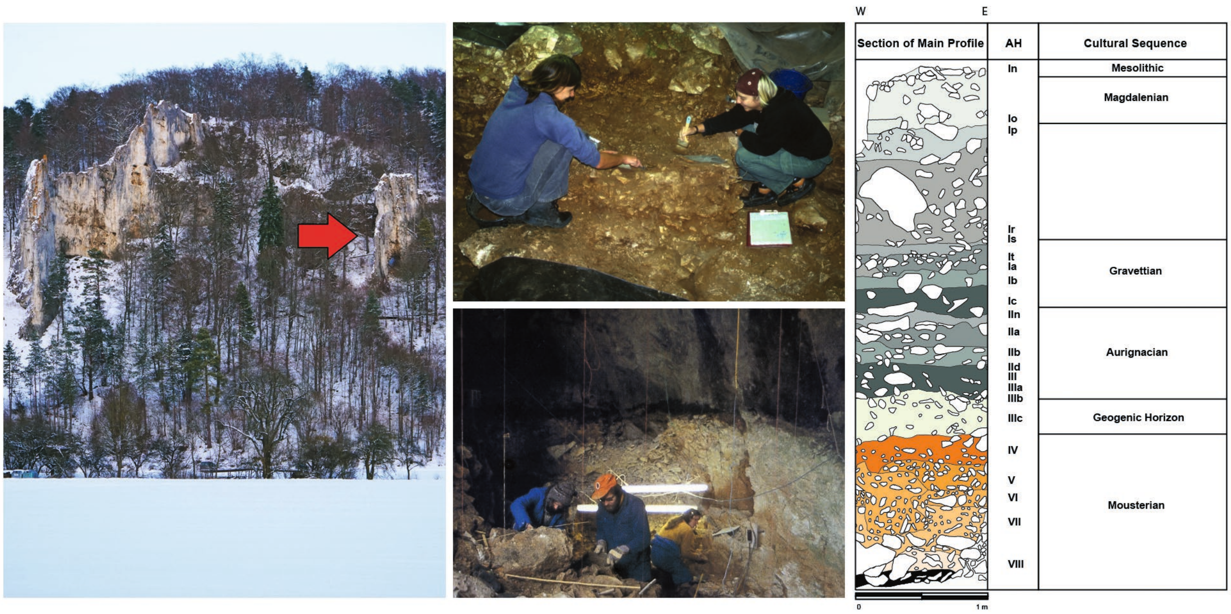

Fig. 2. Composite picture of the site and stratigraphy of Geißenklösterle. Left: View of the collapsed cave of Geißenklösterle from afar (red arrow). Middle bottom: Excavations by J. Hahn (center) with A. Scheer (right; source: Archäologie in Deutschland 1984). Middle top: Excavations into the Middle Paleolithic deposits in 2002 with M. Malina (left) and L. Giemsch (Photo: N. J. Conard). Right: Composite stratigraphy of the main profile for the entire archaeological sequence. The MP layers (AH IV-VIII) are highlighted in colors.

Abb. 2. *Überblick über die Fundstelle und Stratigraphie des Geißenklösterle. Links: Blick auf die eingestürzte Höhle des Geißenklösterle aus der Ferne (roter Pfeil). Mitte unten: Ausgrabungen durch J. Hahn (Mitte) mit A. Scheer (rechts; Quelle: Archäologie in Deutschland 1984). Mitte oben: Ausgrabung in den mittelpaläolithischen Schichten 2002 mit M. Malina (links) und L. Giemsch (Photo: N. J. Conard). Rechts: Stratigraphie des Hauptprofils (idealisiert) für die gesamte archäologische Sequenz. Die MP-Schichten (AH IV-VIII) sind farblich hervorgehoben.*

layers, but opened only a test pit of 4 m^2 for the two uppermost MP levels (AHs IV & V; Hahn 1988) without reaching bedrock. In 2001 and 2002, N. J. Conard continued the fieldwork at GK using Hahn's excavation grid and stratigraphic designations, but added systematic 3D piece plotting of archaeological material with a total station assisted by the EDM program (Dibble & McPherron 1996) to the field methods. The new fieldwork focused on the deeper parts of the deposits (lower Aurignacian III-IIIb and MP layers), with the aim of recovering the entire vertical stratigraphy of the site. These renewed excavations recovered artifacts from all Neanderthal occupations (AHs IV-VIII) in 7-10 m^2 (Fig. 3) and reached bedrock in 6 m^2, uncovering a total thickness of roughly 5 m for the cave deposits (Conard & Malina 2002, 2003; Miller 2015). The majority of the MP assemblages studied here (99 % of lithic artifacts) were excavated with modern field methods by the excavations in 2001 and 2002.

The overall stratigraphy of the site encompasses 23 geological horizons (GHs), among which 20 AHs could be distinguished (Fig. 2; more details in Hahn 1988; Conard & Malina 2003; Miller 2015; Conard et al. 2019). The Mesolithic and UP occupations span AHs I-III (Magdalenian, Gravettian, Aurignacian) whereas the MP settlements encompass AHs IV-VIII (GHs 18-23). The MP deposits lie below a largely geogenic horizon of ca. 20 cm thickness (GH 17; AH IIIc) that separates the Neanderthal occupations from the early Aurignacian (Fig. 4). The stratigraphic discontinuity between the Aurignacian and uppermost MP layers is further attested by differences in lithic and faunal assemblages, a drop in find densities for all classes of finds at the base of the Aurignacian and 3D-plots of finds showing no overlap between the mostly horizontal archaeological horizons (Fig. 4; Conard & Malina 2002, 2003; Conard et al. 2006; Conard et al. 2019).

The MP deposits amount to ca. 1.0 m, which include AHs IV-VIII that range in thickness from 10-35 cm. These five layers are characterized by varying quantities of limestone rubble in a silty matrix which contained variable, but generally low amounts of lithic artifacts, modified faunal remains and burnt bone. The archaeological material did not form clearly defined find horizons and no archaeological features were discerned (Fig. 4), as was also the case in later years at the MP deposits of Hohle Fels (Conard & Malina 2013). Previous observations on sediments, artifacts and extensive refitting (Hahn 1988) revealed that the original positions of stone artifacts and bones have been moved by cryo- and bioturbation after primary sedimentation, which also caused edge damage on lithics (Hahn 1988). Micromorphological studies have, however, found no mixing between the MP and UP layers (Miller 2015; Goldberg et al. 2019). The absence of diagnostic Aurignacian artifacts in the MP layers and the failure to produce any links between the Aurignacian and MP strata during refitting of

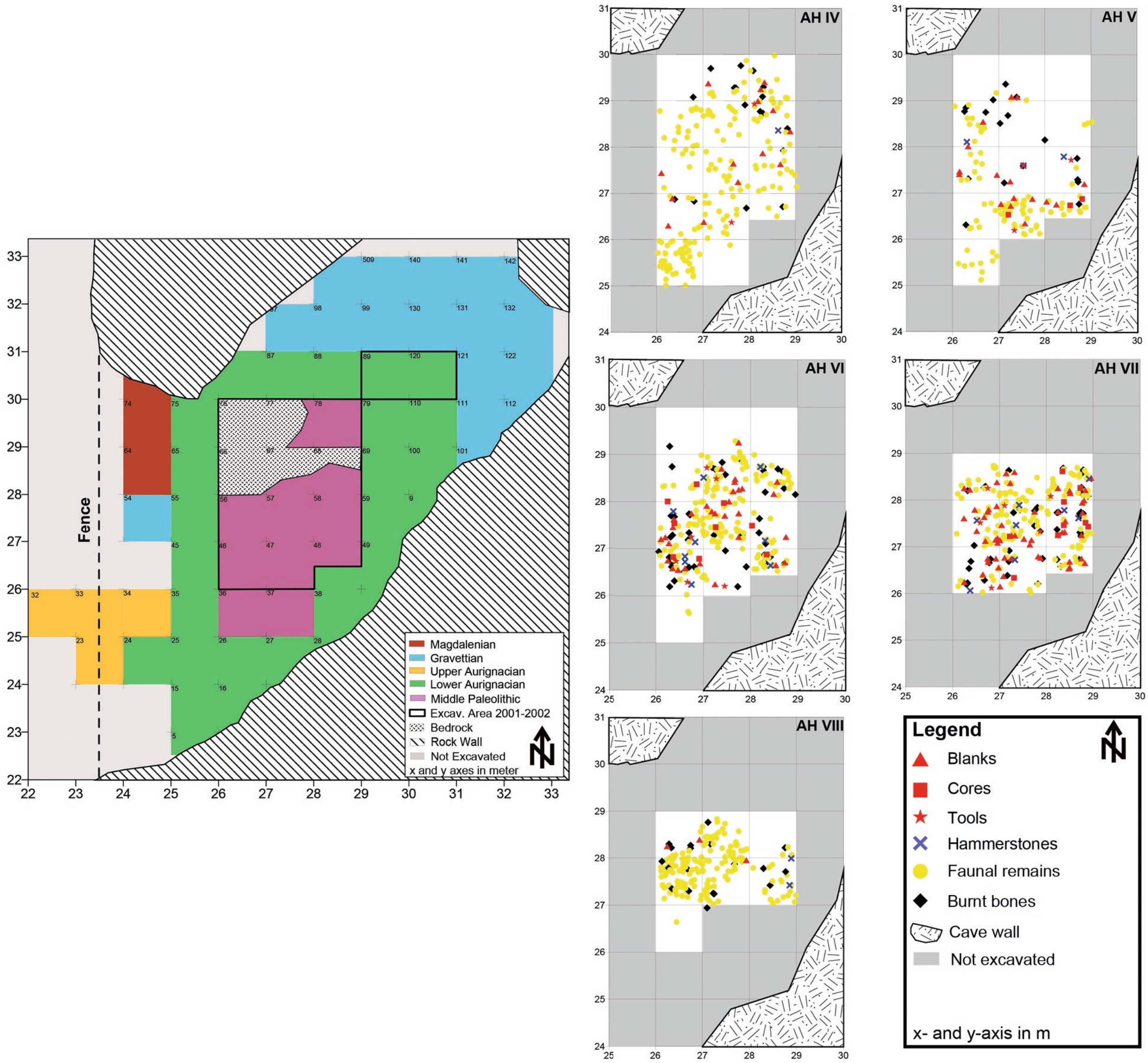

Fig. 3. Overview on the excavation grid of Geißenklösterle with color indication of the different stratigraphic levels reached (left) (after Conard et al. 2019). Horizontal find distribution for faunal remains and stone tools within the five MP find horizons (right) (after Conard and Malina 2003).

Abb. 3. *Messnetz des Geißenklösterle mit farbiger Anzeige der unterschiedlichen stratigraphischen Tiefe, die ergraben wurde (links) (nach Conard et al. 2019). Horizontale Fundverteilung der Faunenreste und Steinartefakte innerhalb der fünf MP-Schichten (rechts) (nach Conard und Malina 2003).*

faunal remains and lithic artifacts (Hahn 1988; Conard & Bolus 2003, 2008; Teyssandier et al. 2006) further attest to the integrity of the Neanderthal occupations.

Given the lack of clear anthropogenic features or stratigraphic markers, the AHs in the MP do not represent occupation horizons in a strict sense. They simply refer to the artifacts from a volume of material from a geological unit of similar composition. These AHs can be viewed as palimpsest from different phases of occupation at GK, and it is best to view the term AH as a technical term. Unlike in the Aurignacian deposits, where refitting sequences and other approaches can be used to critically access the validity of the AHs (Hahn 1988), the lack of long reduction sequences and the low densities of cultural material in the MP horizons makes it difficult to make such assessments. Additionally, stratigraphic ambiguities when excavating deposits lacking clear stratigraphic markers, warn against viewing these AHs as more than a collection of finds of roughly similar age (Hahn 1988; Conard et al. 2019).

Absolute dating of the MP layers has proven to be difficult. Initial absolute dating of the MP horizons by ESR on teeth from Hahn's excavations produced a weighted mean age for AH IV of 43.3 ± 4 ka, placing the final Neanderthal occupation close to beginning of the Aurignacian at the site as well as the Hengelo Interstadial (Richter et al. 2000). Initial radiocarbon dates for the MP horizons IV, VI, VII, and VIII fell between 42 and 31 ka BP (Conard & Bolus 2008) but were considered to be younger than their actual age due to possible taphonomic reworking and potential problems related to elevated levels of atmospheric

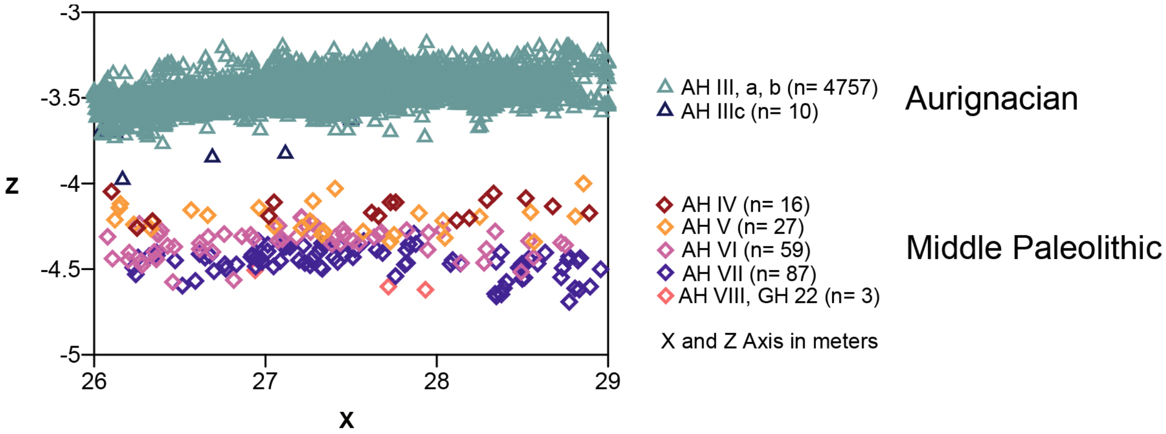

Fig. 4. Vertical distribution of lithic artifacts (piece-plotted number per AH in brackets) from the lower Aurignacian (AH IIIa, b), largely geogenic deposits (AH IIIc) and the MP (AH IV-VIII) of Geißenklösterle (modified after Conard et al. 2006).

***Abb. 4.** Vertikale Fundverteilung von Steinartefakten (Anzahl einzeln eingemessener Stücke pro AH in Klammern) aus dem unteren Aurignacien (AH IIIa, b), der größtenteils geogenen Schicht (AH IIIc) und dem MP (AH IV-VIII) des Geißenklösterle (modifiziert nach Conard et al. 2006).*

radiocarbon ("MP Dating Anomaly", see Conard & Bolus 2008; Higham et al. 2012). More recently, the application of improved AMS ^{14}C dating with an ultra-filtration protocol has provided uncalibrated dates of 35.5 ± 0.65 ka BP for AH IV and 48.6 ± 3.2 ka BP for AH VII (Higham et al. 2012, 2014). Using IntCal13 calibration curves (Reimer et al. 2013) and Bayesian modelling for the lower horizons of GK – taking into account stratigraphic succession and ^{14}C dates from AHs III-VI – provide a final boundary for the end of the MP at the site of 43.8-41.6 ka calBP (Higham et al. 2012, 2014), lying close to the ESR readings from Richter et al. (2000). Based on these dates, the majority of the MP sequence (IV-VII) can be constrained to ~52-43 ka BP, indicating late Neanderthal occupations that mostly fall into MIS 3. The most recent ESR dates by M. Richard provide a somewhat different result, yielding older ages for AHs IV-VIII that range between 55 ± 6 and 65 ± 8 ka BP (AH IV) until 73 ± 10 and 94 ± 10 ka BP (AH VII), pushing particularly the lower part of the sequence well into MIS 5 (see Richard 2015; Richard et al. 2019). The occupation hiatus (GH 17) is dated to 48-44 ± 6 ka BP, providing a minimum age for the MP that is similar to the Bayesian ^{14}C model. AH VIII remains to be dated. In sum, the MP sequence is constrained by several dating methods to between ~94-43 ka BP. While the uppermost layers fall into early and middle MIS 3 relatively close to the arrival of the earliest modern humans, the deeper layers appear to provide a much greater time depth for the entire sequence extending until MIS 5c/d.

Materials and methods

The Middle Paleolithic assemblages of Geißenklösterle

The MP assemblages from GK derive from a total of five archaeological horizons (IV-VIII) that were excavated in 7-14 m² with a volume of 9.5 m³ (Fig. 3). The combined material from Hahn's and Conard's excavations encompass stone artifacts (n = 904), faunal remains (mammalian fauna: NISP = 1 308; g = 6 719.3), modified bone (n = 33; e.g. butchery marks on *Capra ibex*), burnt bone (141 g) as well as charcoal (n = 1; see also Münzel & Conard 2004; Conard et al. 2012; Münzel 2019). Assemblages IV-VIII feature numerous remains of cave bear (n = 586), some hyena (n = 8) and other medium-sized carnivores, whereas the anthropogenic fauna at GK is dominated by remains of reindeer (n = 53), horse (n = 21) and ibex (n = 20) among others (Münzel 2019). For this study, we analyzed all lithic artifacts excavated by Conard (n = 892) and the pieces recovered by Hahn (n = 12 from AHs IV and V; see Hahn 1988). We only recorded artifacts that could be attributed unambiguously to a single archaeological layer. These assemblages include 904 stone artifacts – n = 200 larger than 20 mm and n = 704 smaller than 20 mm, the latter including many microflakes <5 mm (n = 92) – from all archaeological horizons (AH IV-VIII) which vary strongly in sample size (Fig. 5). While layers VI and VII provide reliable sample sizes (n = 238-477), the topmost (IV, V) and lowermost assemblages (VIII) only exhibit small samples (n = 40-85) for artifacts >20 mm. Thus, we consider layers VI and VII to be the most representative assemblages to characterize the MP technology at GK. In relation to sediment volumes, lithic densities are very low (23.7-146.3 n/m³) and contrast markedly with the situation in the overlying UP (mean = 684 n/m³; see Conard et al. 2012). Lithic densities in the MP correlate strongly with total assemblage size, with comparatively high values for layers VI and VII (n/m³ = 112-146) and much lower figures for IV, V and VIII (n/m³ = 24-47). These values suggest that the average occupation density is low, but with some variation.

Layer	Blank	Tool	Core	Angular debris	Hammerstone	Manuport	Small debitage (<20 mm)[1]	Total
AH IV	10 (59 %)	2 (12 %)	0	3 (18 %)	1 (6 %)	1 (6 %)	23 (1)	**40**
AH V	13 (48 %)	3 (11 %)	3 (11 %)	4 (15 %)	3 (11 %)	1 (4 %)	37 (3)	**64**
AH VI	28 (51 %)	6 (11 %)	9 (16 %)	4 (7 %)	7 (13 %)	1 (2 %)	183 (5)	**238**
AH VII	62 (67 %)	6 (7 %)	9 (10 %)	3 (3 %)	8 (9 %)	4 (4 %)	385 (16)	**477**
AH VIII	4 (44 %)	0	0	0	2 (22 %)	3 (33 %)	76 (1)	**85**
Total	**117 (59 %)**	**17 (9 %)**	**21 (11 %)**	**14 (7 %)**	**21 (11 %)**	**10 (5 %)**	**704 (26)**	**904**
	(N) = Number of identified retouch debitage pieces in brackets							

Fig. 5. Numerical distribution (n) of analytical categories for single finds (>20 mm) in each AH. Percentage values (%) are calculated only for single finds (>20 mm).

Abb. 5. *Nummerische Verteilung (n) der Einzelfunde (>20 mm) nach Fundkategorie je AH. Prozentangaben (%) beziehen sich ausschließlich auf die Einzelfunde (>20 mm).*

Raw material availability in the MP of the Swabian Jura

Much previous Paleolithic research in the Swabian Jura has focused on the identification of raw materials and their sources (Beck 1999; Böttcher et al. 2000; Burkert 2001; Çep & Waiblinger 2001; Burkert & Floss 2005; Fisher et al. 2008; Çep et al. 2011; Floss et al. 2012; Çep 2013; Floss & Schürch 2015; Herkert et al. 2015). The lithic raw materials from most MP sites in the region are dominated by local, predominantly grey and white, variants of Jurassic cherts (*Jurahornstein*), with lesser quantities of cherts with different coloration (e.g. Jurassic chert with brown coloration from stratification with bean ore called *Bohnerzhornstein*), radiolarite (green and red variants), black alpine microquartzite (e.g., from the fluvial sediments of the Alpine foothills), quartz and others.

Concerning GK, several known sources for the local light-grey and banded Jurassic chert, such as Borgerhau, are less than 5 km away from the site (Fisher et al. 2008; Floss & Schürch 2015). The Jurassic cherts of the region are accessible in large quantities of nodules – ranging from roughly golf ball to soccer ball-size – and are generally of good but varying knapping quality, appearing in different stages of silicification. The sources for the less frequently used rock types such as *Bohnerzhornstein*, radiolarite and quartzite can usually be found within ca. 20 km of the Swabian caves – often as rounded cobbles from secondary deposits such as river terraces – with no MP site having more than 5 % of finds that come from over 20 km away

Methods of lithic analysis

The study of the lithic assemblages proceeded by AH as principle unit of analysis. All lithic finds >20 mm (n = 200) were examined individually, regardless whether broken or not, with quantitative analyses being performed for the remaining artifacts <20 mm (n = 704). Concerning methods, we combined quantitative attribute analysis with a more qualitative *chaîne opératoire* approach for all lithics >20 mm. Attribute analysis on debitage products (Auffermann et al. 1990; Hahn 1991; Tostevin 2003; Odell 2004) informs on technological behaviors by providing quantitative data of the numerous traces on individual artifacts that result from the knapping process. Our database consisted of ~50 discrete and metric attributes on all debitage products (Fig. 6). Individual stone artifacts and attributes on these pieces constitute the unit of analysis in this approach. For broken pieces, we recorded only preserved attributes and linear measurements (e.g. platform dimensions on proximal fragments), with absent characteristics and dimensions being classified as not assessable (*na*). Summary statistics were thus performed on all recorded attributes, with *na*-coding not featuring in the sample size of the respective data analyses. While recorded on all lithics, we use weight (in g) in further analyses only for complete pieces. All recorded attributes are entered into an Access Database, allowing for subsequent quantitative and statistical analyses on the assemblage level or selected samples. Analyses of collected data were conducted in Excel and SPSS to calculate measures of central tendencies and dispersion for individual attributes, and to conduct further analytical tests. We also identified and quantified lithic products <20 mm by raw material and retouch debitage, as this size class was the most frequent at GK. This approach aids in calculating find densities, evaluating patterns in the raw material economy and quantifying the level of on-site tool production and recycling.

The more holistic and interpretative approach of the *chaîne opératoire* – or reduction sequence analysis – was used to identify the main core reduction methods and the stages of production, use and discard of stone artifacts performed on-site (Boëda et al. 1990; Inizan et al. 1995; Conard & Adler 1997; Soressi & Geneste 2011). These predominantly qualitative and hermeneutic analyses operate on the level of entire assemblages and raw material units. Due to the previously established dominance of Jurassic chert in all MP assemblages at GK (e.g. Conard & Malina 2002, 2003), the approach was principally carried out on the level of individual AHs. We developed diacritic schemes based on close reading of individual artifacts in order to recover more detailed qualitative

All lithics	Blank	Tool	Core
Raw material category	Blank type	Tool type	Clast type
Raw material variety	Diagnostic category	# Retouched edges	Unified core category
Cortex proportion	Completeness	Type of retouch	MP core category
Edge damage	Morphology	Location of retouch	End product
Patina	Bulb	Delineation of retouch	Length of last end product
Frost damage	Contact Point	Side of retouch	Last action
Fire damage / Burning traces	Lipping	Distribution of retouch	# Removal surfaces
	Hertzian cone		Orientation negatives on removal surface
	Shattered bulb		# Platform surfaces
	Platform type		Orientation platform surfaces
	Platform form		Reason for discard
	Platform completeness		Platform preparation
	# Dorsal negatives		Dorsal reduction
	Orientation dorsal negatives		Core exhausted
	Distal end		
	Maximum dimension		
	Maximum length		
	Maximum & 50 % width		
	Maximum & 50 % thickness		
	Exterior platform angle		
	Platform thickness		
	Platform width		

Fig. 6. Discrete and metric attributes recorded for single finds >20 mm at Geißenklösterle by lithic category.

Abb. 6. *Merkmalskatalog der aufgenommenen diskreten und metrischen Attribute für alle Steinartefakte >20 mm am Geißenklösterle nach Kategorie.*

information on the temporal and structural organization of removals and hence specific reduction systems (Dauvois 1976; Inizan et al. 1995; Soressi 2002) which are of particular interest in MP technologies.

Following a holistic approach to lithic analyses in which multiple independent sources of evidence converge to produce more inter-subjective and reliable results, the findings derived from these methods are combined and subsequently used for both intra- and inter-assemblage comparisons. The analyses aim to identify diachronic and synchronic variability in Neanderthal technology at the site and characterize mobility and land-use strategies.

Results

Taphonomy

The size distribution of lithic artifacts (Figs. 5 & 7) indicates a relation of finds <20 mm to those >20 mm of almost four to one, with an abundance of small chipped pieces <10 mm (n = 488). Lithics <20 mm constitute over half of all pieces in all assemblages, with AHs VI-VII exhibiting >75 %. These observations suggest on-site stone knapping by Neanderthals at GK, though in reduced amount compared to experimental Paleolithic assemblages produced by similar methods (e.g. Bertran et al. 2012). Considering the continuous presence of microflakes <5 mm (total n = 92) throughout the MP sequence (Fig. 7), there has not been a major impact of size-sorting by taphonomic processes such as the removal of the smallest particle sizes. The representativeness of the lithic assemblages also results from the application of modern methods of excavation and sieving of all sediments. The MP artifacts demonstrate marked and frequent evidence for frost and sediment damage (i.e. cryoturbation) on a total of 69 % artifacts >20 mm,

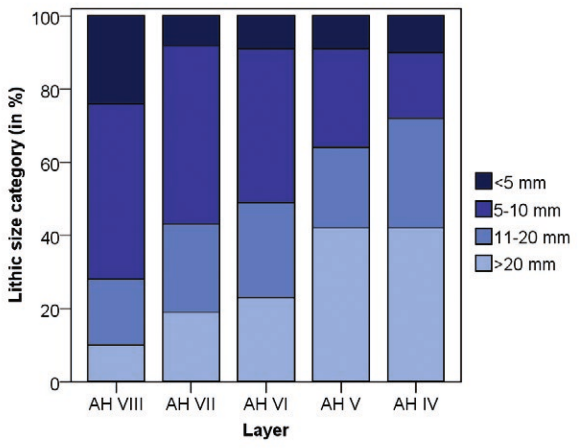

Fig. 7. Histogram of lithic size categories (%) in each AH.

Abb. 7. *Histogramm der Größenverteilung von lithischen Artefakten (in %) je AH.*

with these traces being similarly abundant throughout the entire sequence (67-71 %). Sediment modifications are also present on 56 % of the bone's number of individual specimens (Münzel & Conard 2004). Frost damage on lithic artifacts is particularly frequent in the uppermost layers IV and V (26-29 %; see also Hahn 1988: 102-103; Conard & Malina 2002, 2003).

A higher geogenic input for the uppermost layers is also suggested by the low proportion of debitage products <20 mm (~58 %) compared to strata VI-VIII (77-89 %), that also applies when only considering pieces <10 mm (IV-V: 48-62 %; VI-VIII: 67-80 %). There is also a diachronic trend of increasing numbers of angular debris throughout the sequence – with many frost shatters – without an associated change in raw material use, suggesting a higher degree of disturbances and taphonomic processes damaging pieces at the top of the depositional sequence. There is, however, no evidence for edge rounding or of taphonomic processes introducing or removing artifactual material. While the excavations did not uncover clear hearth structures, the use of fire is attested by the rare occurrence of charcoal (0.12 n/m^3), and more frequent burnt bone (14.2 g/m^3; Conard et al. 2012), as well as traces of heating on 6 % of lithics >20 mm and 5 % of pieces <20 mm. Heated artifacts and densities for charcoal and burnt bone are most frequent in the larger lithic assemblages of VI and VII and virtually absent in the deepest (IV) and uppermost layer (VIII).

Assemblage composition

The assemblages are characterized by a low number of finds >20 mm, ranging from a minimum of 9 pieces (AH VIII) to a maximum of 92 lithics (VII). AHs VI (n = 55) and VII (n = 92) are the largest and most robust samples for the sequence. The quantitative analysis of debitage products for assemblages IV-VIII shows a relatively homogeneous distribution of products with little diachronic change (Fig. 5), supported by a non-significant chi-square test in AH IV-VII for the numerical distribution of blanks and retouched pieces (χ 2(df = 3) = 2.30, p = 0.51). Much of the variation can be accounted for by the very low sample size in the top and particularly lowest layers (AHs IV and VIII). Unretouched blanks are the most frequent category in all layers (44-67 %) except for AH VIII. Retouched pieces (total n = 17) are absent in AH VIII but increase throughout the sequence (6.5-11.8 %), with an overall proportion of tools at 8.5 %. Cores are well-represented for the middle of the sequence (V-VII: 10-16 %; total n = 21) but are lacking in the upper- and lowermost stratum. The consistent increase of angular debris throughout the sequence, from 0 % in VIII to 18 % in IV, is likely due to taphonomic processes (see above). A remarkable feature of the MP assemblages of GK is the high number of cobbles and broken cobbles (total n = 31), most of which show traces of use as hammerstones (see also Pop et al. 2018 more generally). They make up ~16 % of all finds >20 mm, are found equally frequent throughout most of the sequence (IV-VII: 12-15 %) and are particularly numerous in the lowermost assemblage VIII (56 %).

Artifacts <20 mm are abundant in each MP assemblage, particularly in the lower sequence (AHs VI-VIII: 77-89 % of all lithics; Figs. 5 & 7). For most of these layers (V-VIII) artifacts in the size range of 5-10 mm are the most frequent size class and microflakes (<5 mm) also occur throughout the deposits. Although early stages of decortification and core preparation are under-represented and refitting sequences are lacking, the presence of all technological products – blanks, tools, cores, angular debris – document partial reduction sequences with some knapping taking place on-site. The proportion of small retouch flakes among artifacts <20 mm ranges between 1-8 %, throughout the sequence (total: n = 26; 3.7 %) suggesting occasional on-site tool production and curation.

Raw material procurement

All layers exhibit similar proportions of raw materials (Fig. 8), supported by a non-significant chi-square test of counts for Jurassic chert vs. all other raw materials in layers AH IV-VII (χ^2(df = 3) = 1.61, p = 0.66). Conforming to expectations from previous studies, locally acquired rock types dominate, with no chipped lithics coming from further than 20 km away from the site. Light-grey and white Jurassic chert dominates overall (92.9 %) and in each assemblage with >87 %. Assemblages with sample sizes n>30 (AHs VI & VII) exhibit between 91.5-95.0 % of this rock type. Chipped pieces of Jurassic chert show a large range of sizes up to 70 mm but are on average small (~27.4 mm mean length of blanks). Artifacts of Jurassic chert frequently possess cortical surfaces (57 %), which stem predominantly from primary nodules.

Other raw materials occur rarely (Fig. 8). They include *Bohnerzhornstein* (3.6 %; n = 6), *Muschelkalkhornstein* (1.2 %; n = 2), quartzite (1.2 %; n = 2), and green radiolarite (1.2 %; n = 2). None of these raw materials occur in every layer of the sequence, they never reach >7 % in any of the MP assemblages and the lowest layer is devoid of these rock types. Rare cortical surfaces are predominantly smooth and rounded, indicating procurement of cobbles from secondary river channels and terraces. The raw materials of the hammerstones (n = 21) provide a deviating picture from the chipped lithics. Here, Neanderthal toolmakers mostly used Cretaceous quartzite (62 %), which is found throughout almost all assemblages. Other rock types employed for the use as hammerstones include sandstone and quartz (14 % each) as well as rare red radiolarite and quartzite (5 % each).

Blanks

Neanderthal knappers almost exclusively manufactured flakes, dominating overall (94 %) and in each AH (75-96 %), with blades playing a minor role for the total assemblages (n = 8; 6 %). The proportion of flakes

	AH IV	AH V	AH VI	AH VII	AH VIII	Total
>20 mm						
Jurassic chert	13 (87 %)	21 (91 %)	43 (92 %)	76 (95 %)	4 (100 %)	**157 (93 %)**
Bohnerzhornstein	1 (6.5 %)	1 (4.5 %)	0	4 (5 %)	0	**6 (4 %)**
Muschelkalkhornstein	0	0	2 (4 %)	0	0	**2 (1 %)**
Quartzite	1 (6.5 %)	0	1 (2 %)	0	0	**2 (1 %)**
Radiolarite	0	1 (4.5 %)	1 (2 %)	0	0	**2 (1 %)**
<20 mm						
Jurassic chert	22 (96 %)	37 (100 %)	172 (94 %)	366 (95 %)	67 (88 %)	**664 (94 %)**
Bohnerzhornstein	0	0	1 (0.5 %)	9 (2.5 %)	2 (2.5 %)	**12 (2 %)**
Muschelkalkhornstein	0	0	0	0	0	**0**
Quartzite	1 (4 %)	0	4 (2 %)	4 (1 %)	4 (5 %)	**13 (2 %)**
Radiolarite	0	0	6 (3.5 %)	6 (1.5 %)	3 (4 %)	**15 (2 %)**

Fig. 8. Raw material distribution (n) for lithic finds >20 mm and <20 mm in each AH, flaked pieces only.

Abb. 8. *Rohmaterialverteilung (n) der geschlagenen Steinartefakte >20 mm und <20 mm je AH.*

to blades conforms to a homogeneous distribution throughout the entire MP sequence (χ^2(df = 4) = 2.95; p = 0.57). Considering only AHs with a blank sample of n>10, blades never account for more than 8 %, and some appear to be by-products of other reduction strategies that focused on the manufacture of flakes. No convergent flakes, crested blades or bladelets occur among the blanks. A similar pattern is observed when comparing raw materials: Flakes predominate for each raw material (>80 %) with 94.4 % of blanks on the most frequently used Jurassic chert. The few blades were solely manufactured on Jurassic chert (n = 7; 5.6 %) and *Bohnerzhornstein* (n = 1; 20 %).

Most blanks do not exhibit any cortex (44 %), with a further 36 % showing cortical surface values of up to a third of the piece (Fig. 9). Blanks with over a third of dorsal cortex amount to ~20 %. There is only a single fully cortical flake in the total assemblage. Among all blanks, facetted platforms amount to ~27 %, indicating frequent core preparation by the inhabitants of the site. There is an overall chronological trend of decreasing platform preparation, with 24-38 % in AHs VI & VII and markedly lower values in AHs IV & V (11-14 %). The majority of all platforms is plain (~55 %) and only few cortical platforms occur (~9 %). A consistent proportion of ~21-40 % (mean = 30 %) of blanks is complete (n = 52) with the majority being broken pieces.

An important feature of the blanks from the MP at GK is their consistently small size. Overall, knappers manufactured flakes that are on average only ~26 mm long, never exceeding 60 mm. Only 9 % (n = 5) of all measurable blanks are longer than 40 mm. Flakes throughout the sequence V-VIII remain constantly small, ranging between a mean of 20.0-25.6 mm, with AH IV being an outlier with a mean of 38.8 mm. Considering their overall shape and elongation, most blanks (56 %) are slightly elongated. There are no unidirectional temporal trends in elongation throughout the sequence (Kendall rank correlation coefficient: τb = -0.527, p = 0.207; n = 5). From a morphological perspective, most flakes are either of trapezoidal or rectangular shape (85 %), a pattern consistently found in all AHs. A large proportion of flakes possesses backs, formed either by a cortical edge or steep removal scars.

Most blanks exhibit only 1-3 dorsal scars (71 %) with an almost complete absence of pieces with >6 negatives (1 %). Regarding the orientation of dorsal scars, orthogonal (40.8 %) and unidirectional (36.8 %)

Cortex	AH IV	AH V	AH VI	AH VII	AH VIII	Total
0 %	8 (53 %)	9 (39 %)	19 (40 %)	35 (44 %)	3 (75 %)	**74 (44 %)**
1-33 %	4 (27 %)	8 (35 %)	17 (36 %)	30 (38 %)	1 (25 %)	**60 (35.5 %)**
34-66 %	2 (13 %)	4 (17 %)	8 (17 %)	11 (13 %)	0	**25 (15 %)**
67-99 %	1 (7 %)	2 (6 %)	3 (6 %)	3 (4 %)	0	**9 (5 %)**
100 %	0	0	0	1 (1 %)	0	**1 (0.5 %)**
Total	**15**	**23**	**47**	**80**	**4**	**169**

Fig. 9. Numerical distribution (n) and frequency (%) of cortex proportions in each AH.

Abb. 9. *Nummerische Verteilung (n) und Häufigkeit (%) des Kortexanteils je AH.*

patterns dominate, with only a few pieces possessing bidirectional (5.6 %), convergent (2.4 %) or centripetal (1.6 %) negatives. These observations overall suggest that the inhabitants of GK followed a uniform approach to produce predominantly small flakes of rectangular shapes with frequent backs and thereby resulting in asymmetric triangular cross-sections (Fig. 10).

Cores

Only assemblages V-VII have yielded cores (total n = 21). The majority (85.7 %) is made on Jurassic chert, while *Bohnerzhornstein*, *Muschelkalkhornstein* and green radiolarite comprise each 4.8 % of the total cores. In this study, we apply both the unified core taxonomy by Conard *et al.* (2004) as well as a standard MP core taxonomy (e.g. Boëda et al. 1990). According to the unified core taxonomy, parallel cores are the most frequent (57 %), followed by platform (24 %) and bipolar (14 %) types without any clear diachronic trends. Only Jurassic chert features cores for all of these categories. The 12 parallel cores at GK all conform to a Levallois reduction system and include unidirectional (n = 6), preferential (n = 3), centripetal (n = 2) and bidirectional (n = 1) modalities (Figs. 11 & 12). Among all core types, only Levallois is found on all raw materials. The platform cores include single- and multi-platform types, with the single-platform cores exclusively knapped on flakes and corresponding broadly to Kostenki reduction sequences (n = 4; Figs. 11 & 13). We did not observe inclined cores, including discoid, or platform types aiming at laminar production.

The cores predominantly exhibit unidirectional dorsal negatives (47 %) on their main removal surfaces,

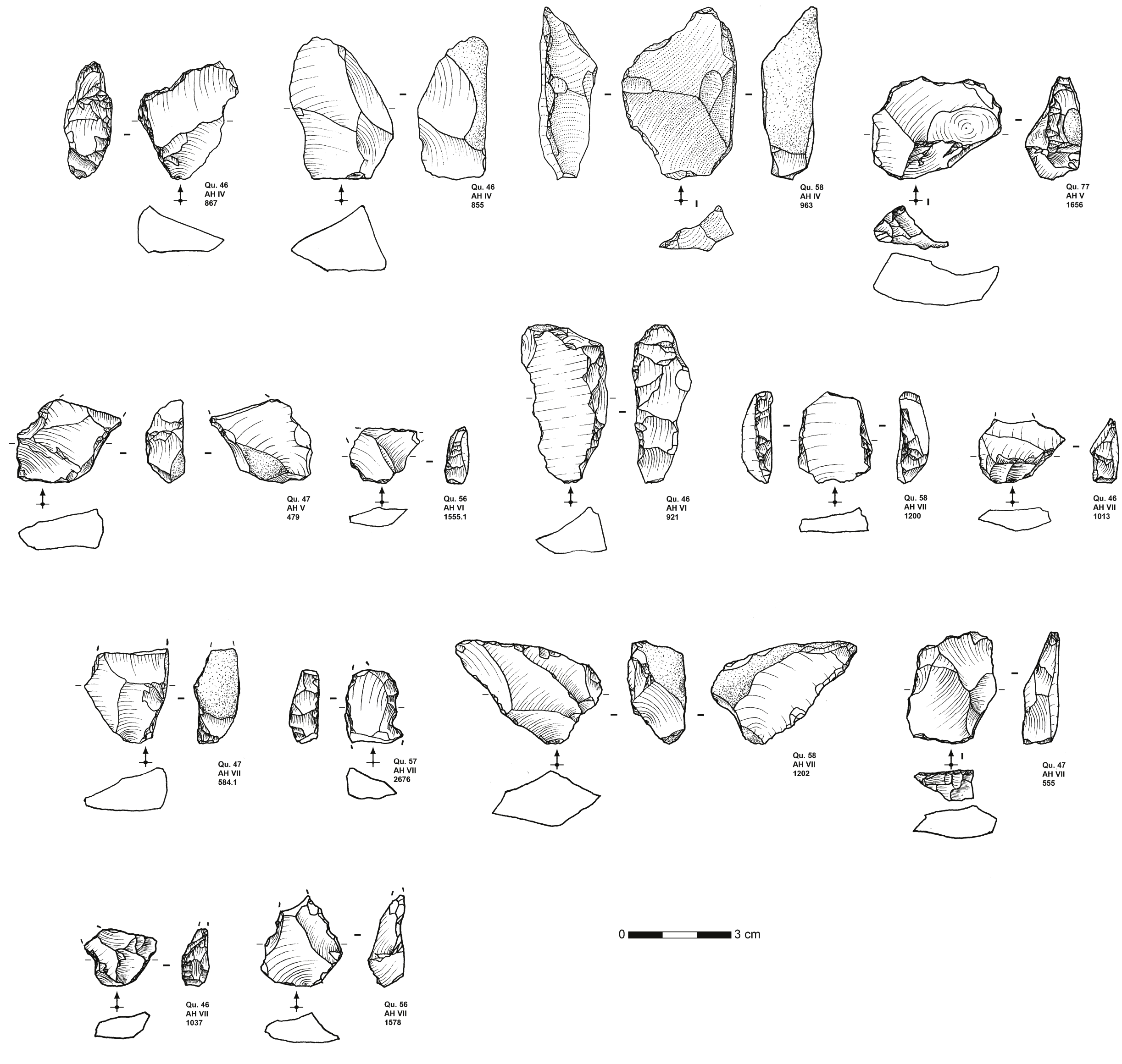

Fig. 10. Levallois core edge flakes (*débordants*) and pseudo-Levallois points from the MP horizons of Geißenklösterle (Drawings by S. Boos and H. Würschem).

Abb. 10. *Levallois Kernkantenabschläge (débordants) und Pseudo-Levallois-Spitzen aus den MP-Horizonten des Geißenklösterle (Zeichnungen von S. Boos und H. Würschem).*

but also a variety of other orientations including preferential (20 %), orthogonal (13 %), bidirectional (13 %) and centripetal (7 %) appear. Preparation of core striking surfaces is common (48 %) consistent with frequent faceting on blank platforms. The cores feature few platform and removal surfaces. Both nodules (n = 9) as well as larger flakes (n = 8) were predominantly used as original core blanks. Whereas over three fourths of the cores exhibit cortex, their extent is mostly between only 1-33 %.

All 21 specimens are flake cores. The cores are small with a median maximum dimension of only 36 mm (mean: 38.1 mm) and a median weight of 13.7 g (mean: 18.7 g), conforming to the small size of blanks. The largest core weighs 95.4 g with a maximum dimension of 70 mm, whereas the smallest core is only 3.0 g and 20 mm. The Jurassic chert cores (n = 18) encompass the largest range but are also small and light on average (median: 35 mm; 11.9 g). The length of the last products on cores averages 19.9 mm (median: 19.5 mm), with a maximum of 37 mm. The small dimensions, high number of removals and the lack of cortex on the main removal surfaces suggest that most of the cores can be considered as being discarded in an exhausted state on-site. A third of the cores were abandoned due to knapping accidents impeding a continuation of the reduction.

Retouched elements

The identification of retouched pieces in the MP of GK is complicated by post-depositional processes which led to frequent edge damage ("cryo-retouch") on 69 % of all pieces. We thus followed a conservative approach that only counted chipped lithics as tools when they exhibit systematic anthropogenic modifications. We define these traces as continuous and preferably multiple generations of retouch scars (preparation, finishing, sharpening) with visible negative bulbs. Our total count of retouched pieces (n = 17) is lower compared to previous assessments (e.g. Conard & Malina 2002). Still, frequencies of tools are relatively high, ranging between 7-12 % per assemblage with exception of the lowermost layer VIII which lacks retouched elements.

From a typological point of view, various types of scrapers are the most frequent tool types (82 %), followed by splintered pieces (18 %) (Figs. 14 & 15). The scraper types encompass frequent side scrapers (n = 9) but also transverse (n = 3), convergent (n = 1) and end scrapers (n = 1). Interestingly, the MP assemblages of the site do not feature denticulates, notches or bifacial implements such as *Keilmesser*. There are also no clear diachronic trends, with scrapers occurring and dominating throughout the sequence (Fig. 14). Tool diversity is low for AHs IV-VII, ranging between 2-3 different types. While all tool types are found on local Jurassic chert, splintered pieces were more frequently made on imported raw materials such as *Muschelkalkhornstein* and radiolarite.

The inhabitants of GK exclusively selected flakes for tool manufacturing with a preference for rectangular or trapezoidal morphologies. Often, these pieces show an asymmetric cross-section with a back opposite to the retouched edge. Many of the retouched blanks are broad and wider than long. Importantly, tools are on average markedly and significantly larger in maximum size compared to unretouched blanks (Mann-Whitney U test: $U = 491.5$; $n = 134$; $p<0.001$), particularly for scrapers that reach a maximum dimension of close to 70 mm. Here, side (mean: 36.3 mm; median 30 mm) and particularly transverse (mean 40.3 mm; median 41 mm) scrapers are on average between 5-10 mm larger than blanks in maximum dimension. Splintered pieces constitute the smallest implements with a mean maximum dimension of only 27.3 mm (median 28 mm) and never exceeding 29 mm.

The knappers applied retouch predominantly to the dorsal face of the blanks (75 %) but also in an alternating fashion (25 %). This retouch remains distributed on the edges of the pieces and does not conform to unifacial or bifacial shaping. Small stepped and scalar negatives are the most abundant modification type. The retouch is often marginal in a convex trajectory along the edge. Secondary modifications rarely include several layers of small overlapping negatives that reach further into the piece. Likewise, retouch usually covers short parts of the artifact edges, but some tools exhibit more than one retouched edge (30 %).

Techniques and methods

The technical act of detaching a flake from a core constitutes a major variable in technological behavior. A total of 63 blanks preserve original platform dimensions. They demonstrate a mean platform thickness of ~5 mm in each assemblage (modal value = 4 mm) with few platforms thinner than 2 mm (1.6 %). Exterior platform angles (EPA) cluster around 83-88°. Based on an assessment of all complete blanks and proximal fragments (n = 72), bulbs are very frequent (94.4 %) and often strongly developed (69 %) with visible contact points on over half of the pieces (53 %). Typical diagnostic features for direct hard stone hammer percussion like Hertzian cones (14 %) and *eraillure* scars (12.5 %) are also present in this sample. Lips occur in very low frequency (1.4 %). The relatively high frequency of longitudinal breaks on flakes (~30 %) is consistent with strong forces exerted by hard stone hammers that had direct contact with the core. Based on these traits on the assemblage-level, blanks in all AHs were predominantly knapped using a hard hammerstone with direct and internal percussion a couple of millimeters away from the core edge (e.g. Pelegrin 2000). In addition, the high frequency of shattered bulbs (25 %) could tentatively suggest some application of soft stone hammers (*pierre tendre*; see Pelegrin 2000; Roussel et al. 2009).

These observations match well with data on the abundant hammerstones and hammerstone fragments throughout the sequence (n = 21). Neanderthals used cobbles from secondary deposits such as river terraces encompassing a wide range of raw materials with most specimens that would be classified as hard (Cretaceous quartzite; quartz; red radiolarite; quartzite; n = 18) and some soft stone hammers (sandstone; n = 3). Fig. 16 depicts the variety of shape and size in hammerstones: often they are elongated, relatively flat and oval in shape. The size of complete hammerstones is variable, ranging from 30-206.7 g (median: 55.5 g), 39-63 mm in maximum dimension (median: 52 mm), 29-63 mm in width (median: 42 mm) and 13-38 mm in thickness (mean: 22 mm). Quartz hammerstones (median: 136.8 g; 66 mm length) are larger compared to the most frequent *Kreidequarzit* specimens (median: 52.4 g; 51.5 mm length). Most hammerstones exhibit one or several pitted surfaces on their edges as macroscopic use-wear from their function (see e.g. Pop et al. 2018). Frequent breakage that split the cobble is a further indication of intense use and then discard of broken stone hammers at the site.

Regarding knapping methods, Neanderthals applied a variety of reduction strategies including Levallois, Kostenki, bipolar and multiple-platform (Fig. 11). Here we provide a more detailed qualitative and holistic assessment of the different reduction sequences based on readings of both cores and flakes. Levallois core reduction is by far the most abundant in both cores and products, followed by some Kostenki reduction and rare use of bipolar and other platform methods. These observations apply particularly to AHs V-VII, with few diagnostic products for the top- and lowermost layers (Fig. 17).

The majority of cores in the MP assemblages (12 of 21) are characterized by two hierarchical, asymmetric and non-interchangeable surfaces, sometimes with intense preparation of the striking platforms (Fig. 12). Knappers used both nodules (67 %) and flakes (33 %) as initial form for these cores. The lower face is often covered with cortex and only sometimes shows preparation removals. Knappers prepared the lateral and distal edges of the core with centripetal removals to create a convex removal surface. The products deriving from this system include central flakes (n = 3) with facetted platforms which have a circular shape as well as orthogonal or centripetal dorsal scar patterns and exhibit EPAs >80°. Products removed along the lateral edges of these cores are very frequent (Fig. 17) and include both core edge flakes (*éclats débordants*, n = 30) and pseudo-Levallois points (*dos limités*, n = 9; Fig. 10). The described cores and flakes conform to a classic Levallois system of reduction (*sensu stricto*; Boëda et al. 1990; Boëda 1993) and encompass various modalities of production. The majority of the cores and respective blanks demonstrates unidirectional recurrent removals (cores n = 6), followed by less frequent preferential (cores n = 3), centripetal (cores n = 2), and bidirectional (cores n = 1) scar patterns (see Figs. 11 & 12). The various modalities occur on small cores (median weight = 13.8 g; range = 9-41.7 g; median MD = 36.5 mm; range = 31-53 mm) that are all in advanced stages of reduction, suggesting the application of multiple reduction strategies is not associated with decreasing core size.

The second most common reduction method encompasses a sub-category of platform cores on flake and amounts to 4 specimens. All of these cores are knapped on flakes of generally small size (weight: mean = 13.0 g; median = 4.8 g; length: mean/median length = 32.0 mm). In this strategy, a single platform is set up on the proximal end of a relatively thick flake (9-15 mm) with a steep inverse truncation of the platform serving as preparation for the subsequent exploitation on the previous dorsal surface of the flake. The striking platforms of these cores are mostly plain. A preparation of the lateral and distal edges occurred on the dorsal surface to create additional longitudinal and transversal convexities documented by small preparation flakes exhibiting a short back and orthogonal removals. The unidirectional reduction of end products on the single main removal surface proceeded along main ridges of the dorsal removals. Knappers removed small and elongated flakes from these core types. The configuration, geometry and

Type	AH IV	AH V	AH VI	AH VII	AH VIII	Total
Levallois unidirectional	0	1	4	1	0	**6**
Levallois preferential	0	0	2	1	0	**3**
Levallois bidirectional	0	0	1	0	0	**1**
Levallois centripetal	0	0	0	2	0	**2**
Kostenki	0	0	2	2	0	**4**
Bipolar	0	1	0	1	0	**2**
Platform	0	0	0	1	0	**1**
Discoid	0	0	0	0	0	**0**
Tested	0	1	0	1	0	**2**

Fig. 11. Numerical distribution (n) of core types in each AH.

Abb. 11. *Nummerische Verteilung (n) der unterschiedlichen Kerntypen je AH.*

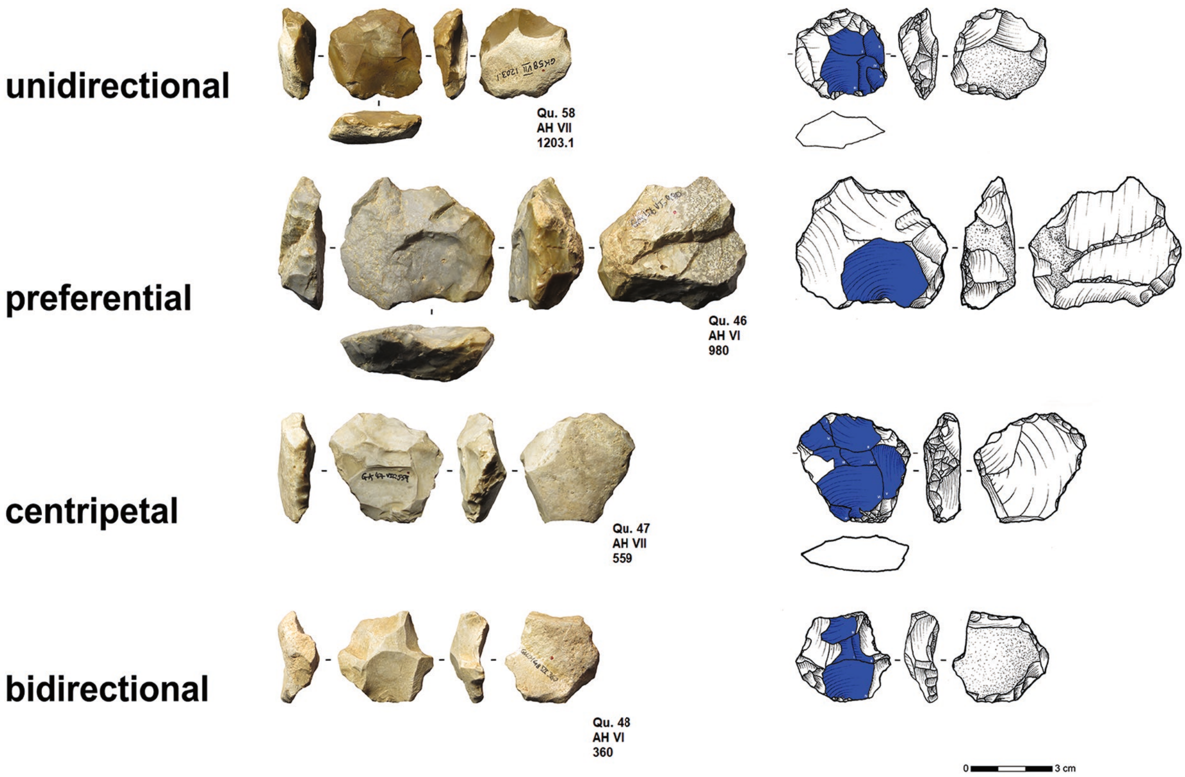

Fig. 12. Various modalities of small Levallois cores from the MP horizons of Geißenklösterle. Levallois flake removals in blue (Drawings by S. Boos and H. Würschem; Photographs by V. C. Schmid).

Abb. 12. *Unterschiedliche Varianten von kleinen Levallois-Kernen des MP aus dem Geißenklösterle. Levallois-Abschläge in blau markiert (Zeichnungen von S. Boos und H. Würschem; Photographien von V. C. Schmid).*

temporal succession of the removals on these cores are depicted in Fig. 13. The described cores fit broadly within the definition of the Kostenki method for the production of small blanks from a dorsal flake surface (e.g. Demars & Laurent 1989; Dibble & McPherron 2007; Frick 2013). The Kostenki reduction sequence at GK corresponds to the use of flakes that originate from a primary production, namely Levallois reduction, as the basis for secondary production paralleling the primary one. These flakes transformed into cores provide a new generation of smaller blanks according to the principle of ramification (see for definition Geneste 1991; Bourguignon et al. 2004). The form of production is considered to be associated with high mobility and a demand for small tools for specific tasks (Rios-Garaizar et al. 2015).

Other platform approaches constitute a third but rare reduction system evident on a single core. This core has two striking platforms adjacent to each other and two removal surfaces located orthogonal to each other, reduced by means of unidirectional, recurrent removals. The negatives of one of the two removal surfaces form the platform for the second removal surface, from which the final flake was removed. Neanderthal knappers set up the core without preparation and established non-hierarchical surfaces by exploiting them successively or alternatively. This double platform type is reminiscent but not identical to Quina reduction (e.g. Bourguignon 1997; Delagnes et al. 2007). The small sample of cores and potential products for this method preclude unequivocal assessment. Finally, rare bipolar reduction rounds out the methods used by Neanderthals at GK. The two cores of this system express impact scars on opposite ends with edge crushing and splintering, and an elongated wedge shape. Small flakes with bidirectional scars are the main products of this strategy. This being said, bipolar products are rare throughout the GK sequence (4.5 %).

Raw material economy

Regardless of their small size, most MP assemblages exhibit products from the majority of the reduction sequences – small debitage, blanks, tools, cores and angular debris. The small samples from layers IV (n = 17) and VIII (n = 9) lack cores, and AH VIII also lacks tools and angular debris with an overrepresentation of hammerstones. Assemblages with larger sample sizes are characterized by more complete reduction sequences, particularly the richer find horizons VI and VII. Some on-site knapping, as well as occasional retouching, are documented by small debitage products and microflakes <5 mm throughout the entire sequence. The low values for cortex on knapped lithics – between 0-7 % pieces with cortical surfaces >70 % and over three fourths with <33 % (Fig. 9) – suggest that little decortification took place at the site which matches the near-absence of large cortical

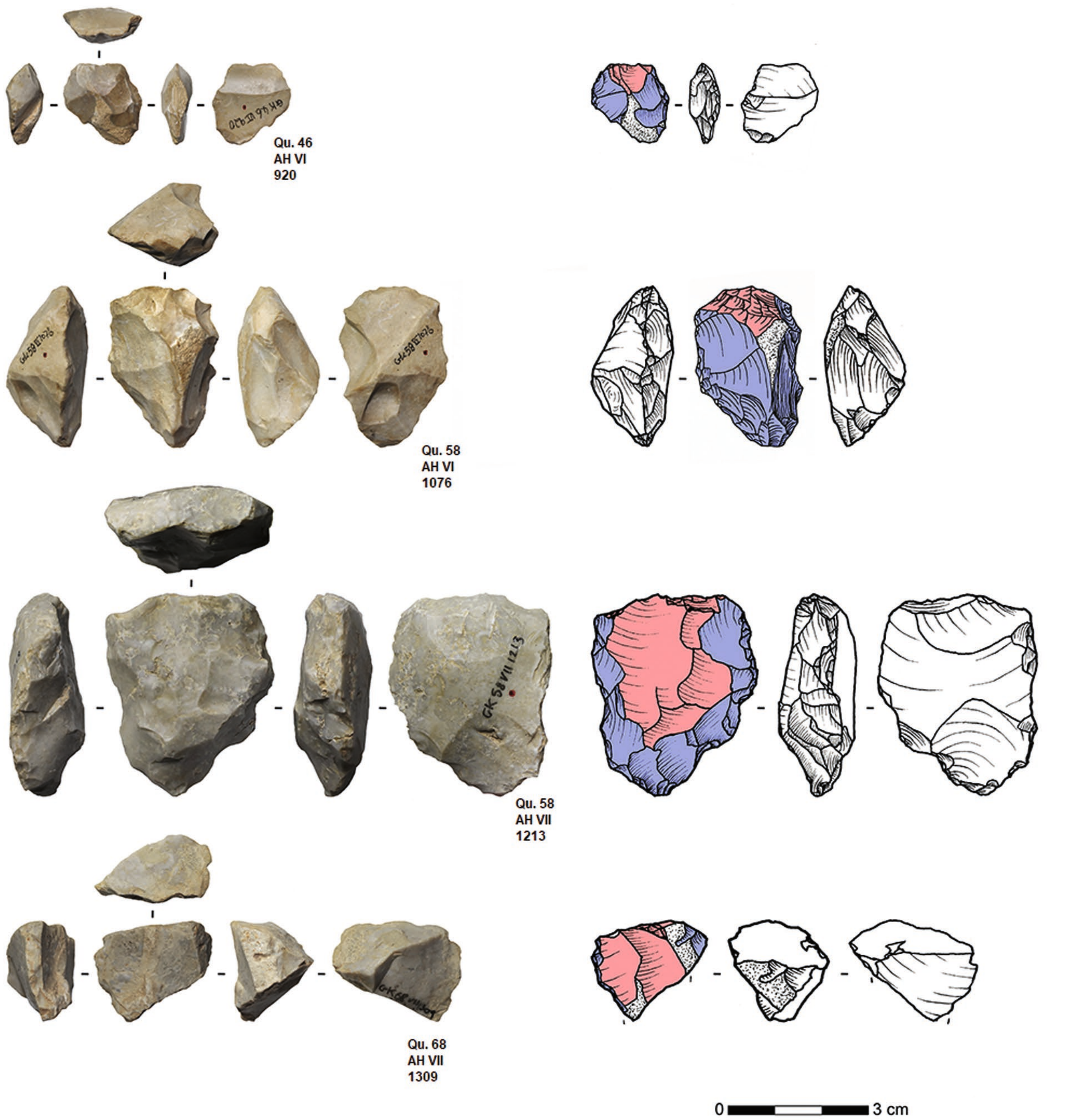

Fig. 13. Kostenki-like cores and reduction concepts from the MP horizons of Geißenklösterle. Dorsal preparation in blue, final removals in light-red (Drawings by S. Boos and H. Würschem; Photographs by V. C. Schmid).

Abb. 13. *Kostenki-ähnliche Kerne und Abbaukonzepte aus den MP-Schichten des Geißenklösterle. Dorsale Präparationen in blau, Zielabschläge in hellrot (Zeichnungen von S. Boos und H. Würschem; Photographien von V. C. Schmid).*

manuports and tested cores. The average size and weight of cores of Jurassic chert (median: 35 mm; 11.9 g) lie well below the average dimensions of the primarily available nodules that range from golf ball to soccer ball size. The assemblages demonstrate a focus on the introduction and reduction of prepared cores in an already advanced state, as well as some production and modification of blanks.

These patterns are associated with export of finished blanks and tools. We observed a conspicuous lack of end-products for the various modalities of the Levallois reduction system: There are 12 Levallois cores with multiple negatives of flake removals, providing evidence for the production of ~20-30 Levallois flakes using a conservative estimate of 2-3 flakes per core. Yet, the combined assemblages only yield three definite central Levallois flakes (*Zielabschlag*) that were left behind in the MP at GK. In contrast, the assemblages are characterized by an abundance of core edge flakes and pseudo-Levallois points (n = 39), which correspond more to preparatory operations. Yet, several of these products were also selected for retouch. This suggests first an export of some finished Levallois flakes from the site, but also indicates the frequent discard of asymmetrical core-edge flakes and their occasional transformation

Layer	Side scraper	Transverse scraper	End scraper	Convergent scraper	Splintered piece	Total
AH IV	1 (50 %)	0	1 (50 %)	0	0	**2**
AH V	1 (33 %)	1 (33 %)	0	0	1 (33 %)	**3**
AH VI	3 (50 %)	1 (17 %)	0	0	2 (33 %)	**6**
AH VII	4 (67 %)	1 (17 %)	0	1 (17 %)	0	**6**
AH VIII	0	0	0	0	0	**0**
Total	**9 (53 %)**	**3 (18 %)**	**1 (6 %)**	**1 (6 %)**	**3 (18 %)**	**17**

Fig. 14. Numerical distribution (n) and frequency (%) of tool types in each AH.

Abb. 14. *Nummerische Verteilung (n) und Häufigkeit (%) unterschiedlicher Werkzeugtypen je AH.*

into scrapers with an opposed back that were discarded on-site (Fig. 18).

A clear pattern of raw material economy can be inferred from the assemblages. Each AH features more or less complete reduction sequences for the local Jurassic chert, indicating its on-site production and re-sharpening. The relatively low number of blanks in relation to cores for this raw material (6.2 blanks per core) also suggests some transport of knapping products to other places in the landscape (see above). In contrast, other raw materials of low abundance and from slightly further away (e.g. *Bohnerzhornstein*, *Muschelkalkhornstein* and radiolarite) are predominantly present as isolated tools and exhausted cores that were likely imported by Neanderthals as single pieces with little to no on-site knapping.

Several lines of quantitative evidence support the qualitative observations of a differential treatment for the frequently used Jurassic chert (93 %) compared to the other raw materials. First, the very low absolute number of *Bohnerzhornstein*, *Muschelkalkhornstein* and radiolarite for each layer (n = 2-6; >20 mm) that also applies to small debitage (n = 12-15; <20 mm; Fig. 8) stands out. Small debitage for *Bohnerzhornstein* (mean: 1.2 %; range: 0-2.6 %) and radiolarite (mean: 1.7 %; range: 0-3.9 %) is proportionally even less frequent compared to products >20 mm, whereas Jurassic chert shows a slightly higher overall proportion of small chipped pieces (94.3 %). There is a high frequency of tools for *Bohnerzhornstein* (17 %), *Muschelkalkhornstein* (50 %) and radiolarite (50 %) compared to Jurassic chert (9 %). Overall,

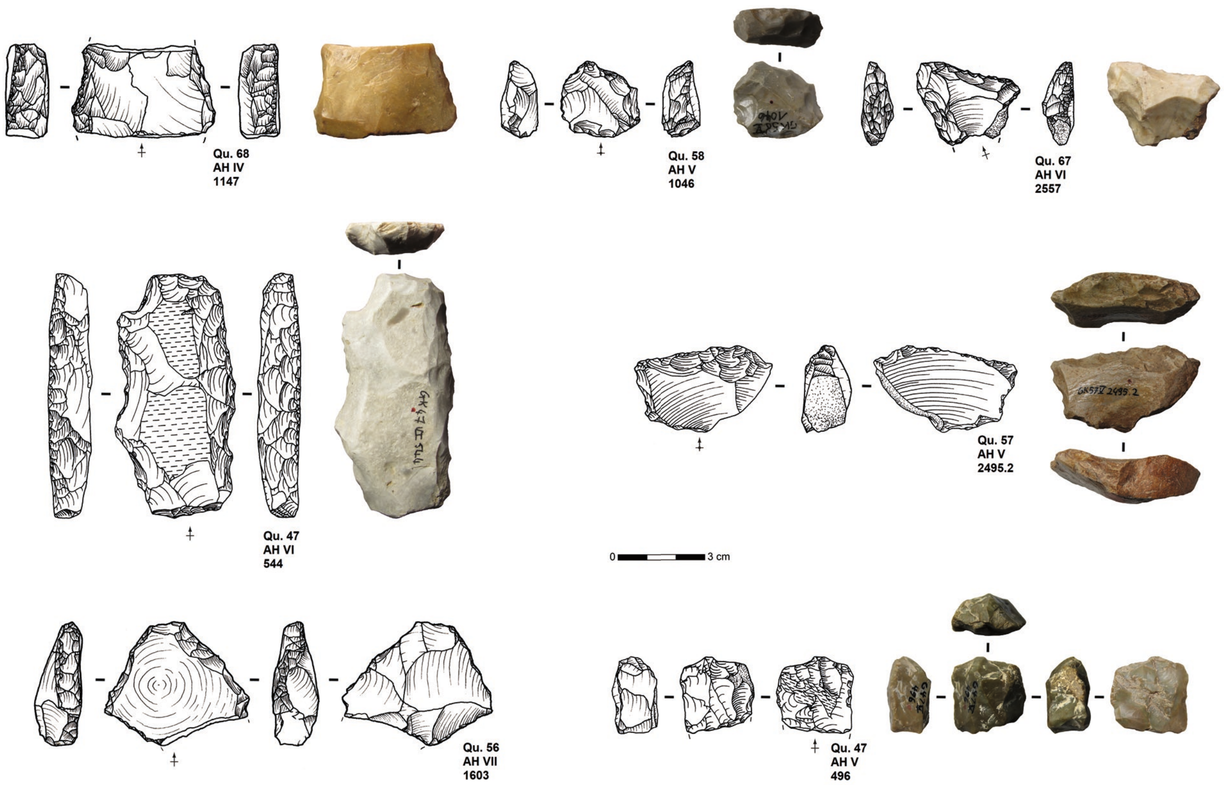

Fig. 15. Selection of tools from the MP horizons of Geißenklösterle. The depicted tools encompass various scraper forms except for a splintered piece in the bottom right (Drawings by S. Boos and H. Würschem; Photographs by V. C. Schmid).

Abb. 15. *Auswahl an Werkzeugen der MP-Horizonte des Geißenklösterle. Die dargestellten Werkzeuge sind unterschiedliche Schaberformen, mit Ausnahme des ausgesplitterten Stückes unten rechts (Zeichnungen von S. Boos und H. Würschem; Photographien von V. C. Schmid).*

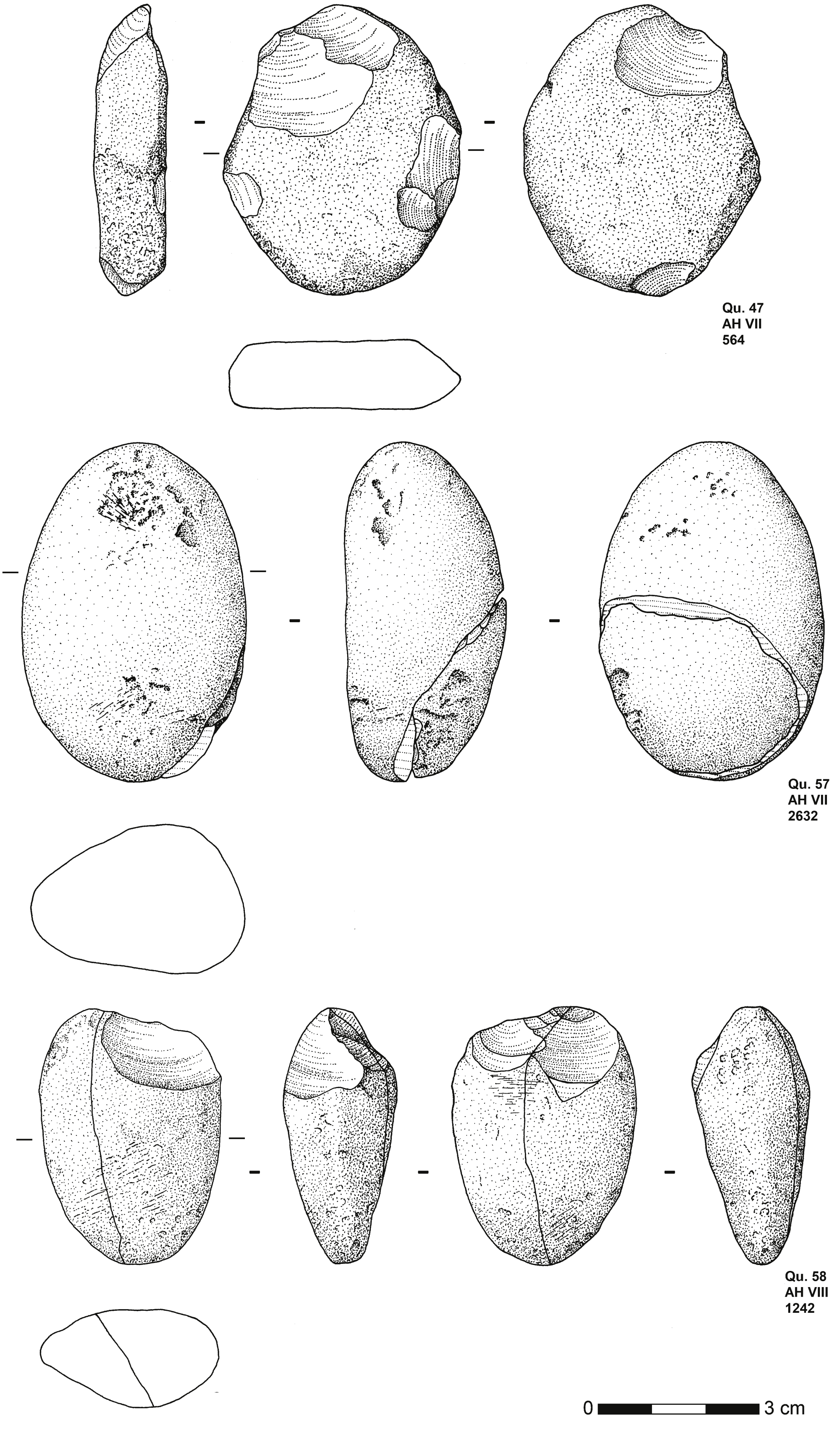

Fig. 16. Selection of hammerstones from the MP archaeological horizons of Geißenklösterle (Drawings by S. Boos).

Abb. 16. *Auswahl an Schlagsteinen aus den MP-Schichten des Geißenklösterle (Zeichnungen von S. Boos).*

Type	AH IV	AH V	AH VI	AH VII	AH VIII	Total
Levallois end product	0	0	1	2	0	**3**
Levallois core edge (*Débordant*)	3	3	5	19	0	**30**
Pseudo-Levallois point (*Dos limité*)	0	1	4	4	0	**9**
Kostenki	0	0	1	0	0	**1**
Bipolar	1	2	1	2	0	**6**
Quina	0	0	1	0	0	**1**
Laminar	0	0	0	0	0	**0**
Bifacial	0	0	0	0	0	**0**
Undiagnostic	8	10	21	40	4	**83**

Fig. 17. Numerical distribution of technologically diagnostic pieces for single finds (>20 mm; except cores) in each AH.
Abb. 17. *Nummerische Verteilung von technologisch diagnostischen Stücken innerhalb der Einzelfunde (>20 mm; ohne Kerne) je AH.*

Bohnerzhornstein, and even stronger *Muschelkalkhornstein* and green radiolarite are overrepresented among the tools (including splintered pieces) in relation to their proportion compared to Jurassic chert. Higher cortex values (>70 %) occur exclusively on Jurassic chert with the majority of the other raw materials showing no or only few cortical surfaces (<33 %). Blanks on *Bohnerzhornstein*, *Muschelkalkhornstein*, radiolarite and quartzite are larger and thicker (mean length = 32-49 mm; mean thickness = 10-15 mm) compared to the generally smaller products from Jurassic chert (mean length = 27.4 mm; mean thickness = 9.9 mm) which were often more strongly reduced on-site. These observations demonstrate a predominantly localized provisioning strategy by the Neanderthal inhabitants focused on the local light-gray Jurassic chert, with rare use of other rock types.

In sum, the data support a techno-economic scenario of several short-term episodes of import, production, retouching as well as resharpening, discard, and export. Thus knapping as well as abandonment of exhausted cores and tools took place at the site, while Neanderthal toolmakers transported desired end-products off-site and carried them as mobile toolkit along from place to place (Porraz 2009), complying with an individual provisioning strategy to cope with immediate and anticipated technological needs (Kuhn 1995, 2004).

Discussion

The MP assemblages of Geißenklösterle: Characteristics and diachronic trends

Our results represent the first comprehensive analysis of the MP artifact assemblages from GK. These numerically small assemblages derive from multiple archaeological horizons in a secure stratigraphy, possess detailed contextual information, and are associated with absolute dates. Based on these features, the MP assemblages at GK provide new insights into Neanderthal technology and lifeways during the Late Pleistocene of the Swabian Jura.

Various Levallois modalities constitute the most frequent core reduction strategies documented in all assemblages. The assemblages, however, feature only few typical Levallois blanks. Neanderthals also used Kostenki-like reduction, and rarely exploited bipolar and platform cores at the site. We, however, have not identified discoid or laminar reduction at the site. The knappers predominantly produced small, elongated flakes of trapezoidal or rectangular shape, often with asymmetrical cross-sections (Figs. 10 & 18). Only a few

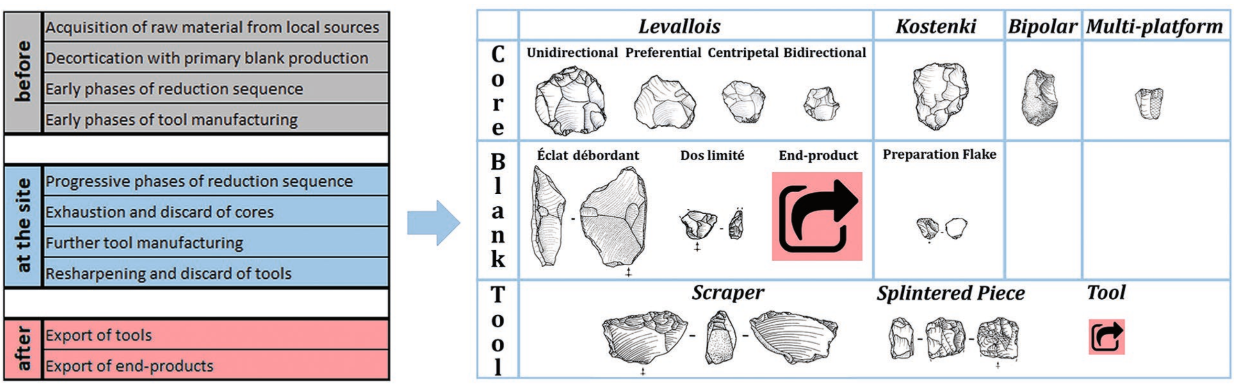

Fig. 18. Summary of the operational sequence discerned from the MP lithic assemblages of Geißenklösterle.
Abb. 18. *Zusammenfassung der Operationskette, abgeleitet aus den MP-Steinartefaktinventaren des Geißenklösterle.*

flakes exceed 40 mm in maximum dimension. The knappers mainly used hard hammer percussion as is attested by a high number of hammerstones from local river cobbles. Different types of scrapers are the most frequent tool types, followed by splintered pieces. Based on what was discarded at GK, Neanderthals preferentially selected relatively large blanks with asymmetrical cross-sections for scraper forms, and applied retouch along the thinner edge of the flakes as a working edge opposite to the natural backing presumably representing a passive or prehensile part. The assemblages completely lack notches, denticulates or bifacial implements such as *Keilmesser* or *Blattspitzen*.

Throughout all layers, the inhabitants predominantly knapped local Jurassic cherts (>90 %) with only small amounts of other raw materials. The assemblages demonstrate relatively complete reduction sequences for Jurassic chert – particularly in AH VI and VII – with a notable underrepresentation of Levallois blanks. A low frequency (2-10 %) of small retouch flakes, along with abundant small artifacts between 5 and 10 mm in size (n = 396) and less frequent microflakes smaller than 5 mm (n = 92) attest to some on-site blank and tool production in the MP horizons of GK (see e.g. Bertran et al. 2012). This pattern stands in contrast to less common lithic raw materials including radiolarite, *Bohnerzhornstein*, *Muschelkalkhornstein* and black alpine microquartzite, which are characterized mainly by isolated flakes and tools from the distal ends of their biographies. Small (n = 30) and micro-artifacts (n = 7) are almost completely absent for these rare raw materials. Thus in contrast to Jurassic chert, artifacts on the less frequent rock types were mostly brought to the site in finished form and then discarded at GK.

The MP archaeological sequence at GK consists of five AHs, allowing diachronic observations. Although our analyses reveal some inter-assemblage variation, there are more similarities than differences in all principle technological domains and raw material use. The remaining diachronic differences likely stem from small sample sizes particularly for layers IV and VIII. The largest assemblages, AH VI & VII, are similar in their techno-typological characteristics. Assemblages IV-VIII from GK appear to represent a stable techno-typological and techno-economic pattern of behavior within the MP of the Swabian Jura.

Geißenklösterle in the context of the Swabian Middle Paleolithic

The MP assemblages from GK offer a well-studied basis for further comparisons on the local and regional level. We are interested in how GK fits within previous work on MP lithic technology in the Swabian Jura and the general cultural stratigraphy of Germany, Central Europe and beyond (see next section). Numerous sites and studies of MP assemblages from the Swabian Jura allow for comparisons (Schmidt 1912; Peters 1931; Riek 1934; Wetzel & Bosinski 1969; Hahn 1988; Beck 1999; Böttcher et al. 2000; Çep & Waiblinger 2001; Conard 2005, 2011; Conard et al. 2006, 2012; Bolus 2011; Çep 2013; Bolus 2015; Çep & Krönneck 2015). Many of these assemblages have not been excavated by modern standards and often lack contextual information, comparable quantitative data and absolute dates. Thus we compare strategies of raw material procurement and techno-typological characteristics of GK to the most important sites of the Swabian Jura as far as data permit.

The assemblages of GK are comparable to many other Neanderthal sites in the Swabian Jura in featuring small assemblages and a low density of lithic artifacts (GK: 24-146 n/m^3), such as Hohle Fels (33-703 n/m^3), Sirgenstein (~20 n/m^3), Kogelstein (203-318 n/m^3), Große Grotte (1-14 n/m^3), and Vogelherd (30-320 n/m^3; density values from Conard et al. 2012; see also Riek 1934; Wagner 1983; Conard et al. 2006, Conard 2011; Bolus 2015). This also applies to other classes of finds. In this regard, GK contrasts sharply with larger lithic assemblages such as Bockstein and Heidenschmiede (Peters 1931; Wetzel & Bosinski 1969; Çep 2014; Çep & Krönneck 2015). Raw material procurement is predominantly local at all MP sites of the Swabian Jura. The overall proportions of Jurassic chert at GK (~93 %) are similar to Hohle Fels (86-96 %; Conard & Malina 2013) but higher compared to other MP sites such as Kogelstein (45 % local Jurassic chert; 75 % all Jurassic chert), Sirgenstein (VII/VIII = 76 %), Hohlenstein-Stadel (62 %), Hohlenstein-Bärenhöhle (85 %) and Große Grotte (63-78 %; data from Beck 1999; Böttcher et al. 2000; Çep 2013: Fig. 4). As is the case at many other sites in the region (Çep & Waiblinger 2001; Çep & Krönneck 2015), incomplete reduction sequences with isolated artifacts characterize the use of rock types other than Jurassic chert at GK.

Regarding general technological aspects, various modalities of the Levallois concept dominate most MP sites of the region, including Hohle Fels, Sirgenstein, Große Grotte, Hohlenstein and Vogelherd. Another unifying feature between these sites and GK is the observation of frequent small and intensely exhausted Levallois cores. Comparable metric data exists for the assemblages at Hohlenstein which provide an average size of prepared cores between ~48-52 mm (Beck 1999: Table 19 & Table 47) with respective cores at GK being even smaller (mean: 37 mm; range: 25-53 mm). The end-products of these reduction systems are also of small size: Levallois flakes at GK lie at an average length ~30 mm and comparable data from Hohlenstein at 36-38 mm (Beck 1999: Table 8 & Table 40). In combination, these characteristics are often used to describe the technocomplex of the "Swabian Mousterian" (Schmidt 1912; Riek 1934; Wagner 1983; Beck 1999; Böttcher et al. 2000; Conard et al. 2006, 2012; Conard 2011; Bolus 2015). While we originally viewed these highly reduced cores and debitage products as characteristic of find horizons in caves like GK and Hohle Fels, preliminary results from

Fröhle's doctoral research suggest that such highly reduced cores are also well represented at open-air sites in Baden-Württemberg (Fröhle et al. 2019). Although Kostenki cores were also reported for the Aurignacian of GK and Vogelherd, here associated with bladelet production (Hahn 1988: 285, Fig. 21.1; Hahn 1991), comparable pieces have not been identified at any other MP sites of the region, documenting an aspect of variability at these sites. This study illustrates a further degree of diversity in reduction strategies at GK, with the presence of bipolar and platform cores.

With a tool proportion of 8.5 % (>20 mm) GK compares well to the MP at Kogelstein (7.2 %; calculated from Böttcher et al. 2000: Table 38 excluding small debitage <10 mm), Sirgenstein (3.8 % in layer VII/VII; Çep 1996), and Hohle Fels (3-8 %; Conard & Malina 2013), but differs strongly from Hohlenstein-Stadel (23.9 %; Beck 1999), Hohlenstein-Bärenhöhle (33.9 %; Beck 1999), and Bocksteinschmiede (~20 %; Çep 2014). Some of these older excavations, however, did not systematically recover small lithics, resulting in a bias towards higher frequencies for retouched pieces. Typologically most similar to GK are MP assemblages attributed to the Swabian Mousterian, defined by an array of diverse scrapers and found at sites such as Hohle Fels, Sirgenstein, Hohlenstein, Große Grotte, and Vogelherd. The observation of larger sizes for retouched compared to unretouched pieces, and thus a selection of larger blanks for further modifications, unites the assemblages from Hohlenstein (Beck 1999: 155) and GK. Yet, GK differs from these assemblages with regard to the occurrence of splintered pieces.

Various bifacial pieces – *Blattspitzen* or bifacially backed knives (*Keilmesser*) – characterize the other main technocomplexes of the region, the *Blattspitzen*- and *Keilmessergruppen* (Richter 1997, 2016; Conard & Fischer 2000; Jöris 2003; Bolus 2004b, 2011, 2015) most notably at Bockstein, Heidenschmiede and Haldenstein (Peters 1931; Riek, 1938; Wetzel & Bosinski 1969; Bolus & Rück 2000; Çep 2014; Çep & Krönneck 2015). While isolated finds of these bifacial artifacts can be found in almost all MP assemblages of the Swabian Jura, complicating their use as chrono-cultural markers (Çep & Krönneck 2015; Herkert et al. 2015), none of the archaeological horizons at GK has yielded bifacially retouched tools or debitage from bifacial shaping. The absence of these products at GK appears to be a distinct aspect of the MP assemblages.

Our local comparisons indicate that the MP assemblages from GK correspond closest to the Swabian Mousterian (Schmidt 1912; Riek 1934; Beck 1999; Conard 2011; Conard et al. 2012; Bolus 2015) – synonymously denoted as "Albhöhlen Moustérien" by some (Wagner 1983: 56). The absence of bifacial technology separates GK clearly from the *Blattspitzen*- and *Keilmessergruppen*. The findings from GK, however, provide additional elements of variability to the definition of the Swabian Mousterian: the exploitation of cores corresponding broadly to Kostenki reduction and to a lesser degree bipolar as well as platform cores and the occurrence of splintered pieces. A re-evaluation of other assemblages attributed to the Swabian Mousterian is required to check whether these aspects are unique to GK – and, if so, why, considering the comparable use of raw materials and other unifying characteristics of assemblages from this technocomplex.

Unlike the other sites in the region, GK provides a rare glimpse into the relative and absolute timeframe of the Swabian Mousterian. Absolute dating at the site indicates that the technocomplex lasted from MIS 5 into MIS 3. The stability and time depth of the Swabian Mousterian is also demonstrated by the five consecutive archaeological layers with similar techno-typological characteristics. At GK the Swabian Mousterian is followed by a largely geogenic horizon, marking the technocomplex as the final Neanderthal occupation at the site and potentially lasting until ~45-43 ka BP (Richter et al. 2000; Higham et al. 2012, 2014; Goldberg et al. 2019). In this regard, the MP from GK has the potential to contribute to the chrono-cultural stratigraphy of Neanderthals in the Swabian Jura and Central Europe.

The MP of Geißenklösterle in a broader geographic context

To what extent is the Swabian Mousterian at GK comparable to the MP in other regions of Central Europe? How can we explain the variable presence or absence of bifacial technological elements in the MP of southwestern Germany and beyond (i.e. cultural, temporal or functional)? In the following, we will restrict ourselves to only the most informative comparative sites relevant to our questions from stratified contexts, with detailed data on lithic assemblages in the timeframe ~90-40 ka and a focus on Germany.

One of the most informative sites on MP assemblages with and without bifacial technology are the well-studied and find-rich assemblages from Sesselfelsgrotte in the Altmühl Valley (Bavaria) close to the Swabian Jura (Weißmüller 1995; Richter 1997, 2016; Freund 1998). The key technological feature of the long cultural stratigraphy of the site (23 MP occupations spanning MIS 5c-3) is the alternation between occupations rich in bifacial technology and those with only a few *Keilmesser* or a complete lack of these pieces in the G-Complex of MIS 3 (*Keilmessergruppen* or Micoquian in the sense of a "Mousterian with a Micoquian option", MMO; Richter 1997, 2016). The bottom of the MP sequence (*Untere Schichten*) dating to the Early Würmian does not feature bifacial technology. Richter (1997, 2016; see also Uthmeier 2004) interprets the interstratification of assemblages with and without bifacial technology in the G-Complex as different functional and seasonal variants within a single settlement system (land-use cycles).

Assemblages poor in bifacial artifacts represent so-called "*Initialinventare*" deriving from initial, explorative occupations of a given region followed by longer and more-specialized settlements ("*Konsekutivinventare*") with bifacial technology, all belonging to the same MMO cultural unit. Importantly, this situation of marked diachronic change in (bifacial) technology contrasts with the assemblages at GK which are consistent in their techno-typological and contextual characteristics throughout and do not feature any bifacial tools or debitage from shaping. Differences to the MMO concept also occur concerning a consistent procurement of raw materials and with regard to reduction strategies, with all GK layers showing evidence for multiple Levallois modalities without a clear presence of Quina methods. High percentages of denticulate tools in small assemblages – expected as markers of *Initialinventare* (Richter 1997, 2016) – are also lacking at GK. Thus the consistent and distinct techno-typological markers for the five assemblages at GK cannot be easily explained as *Initialinventare*.

The site complex of Buhlen in Hessen provides another comparative example. The *Obere Fundplatz*, or Upper Site, yielded rich, stratified *Keilmessergruppen* assemblages (*Schichtkomplex* III; assigned by Jöris (2001, 2003) to late MIS 5a; but see Richter 2016) overlain by layers without bifacial technology (Schicht II attributed to MIS 3), interpreted as a separate Mousterian technocomplex (Bosinski & Kulick 1973; Jöris 2001, 2003). The assemblage from *Schichtkomplex* II shows similarities with the sequence at GK with a focus on various modalities of Levallois reduction and the occurrence of core edge flakes, pseudo-Levallois points, and the production of various types of scraper. The assemblages from the *Untere Fundplatz*, or Lower Site, dated to the Early or Middle Würmian, feature both assemblages without ("Moustérien" similar to Schicht II) and with some bifacial pieces (*Keilmesser* in *Fundkomplex* 4; see Bosinski & Kulick 1973), the latter associated with Levallois and discoid components and a diverse tool kit including backed knives and denticulates (Fiedler 2009). The assemblages from Buhlen-4, like in the sequence from GK, contain artifacts exhibiting Kostenki reduction (*Kostenki-Enden*; Fiedler 2009: 29-31; Taf. 45-51, 56-58) and splintered pieces (Fiedler 2009: Taf. 50). This being said, these assemblages from Buhlen-4 differ from the MP sequence at GK in their laminar component, high frequency of backed bifacial knives (*Keilmesser*) and rare examples of other bifacial artifacts. On the whole, the variable presence of bifacial technology at Buhlen stands in clear contrast to the cultural stratigraphic situation at GK.

The open-air, lakeside site of Königsaue in Saxony-Anhalt (Mania & Töpfer 1973; Mania 2002) provides another instructive example from the MP of Central Europe for interpreting stratigraphic sequences that yield assemblages with (Königsaue Levels A and C) and without or with only few (Königsaue Level B) bifacial elements (*Keilmesser Typ Königsaue*). Recently Picin (2017) interpreted the absence and presence of *Keilmesser* as being directly dependent on mobility systems and site use. All levels are associated with various modalities of Levallois reduction and short-term occupations. However, in level B without *Keilmesser*, Levallois flakes were transported off-site indicating more residential mobility with repeated short visits to this lakeshore setting for flint knapping and other activities according to Picin (2017). In contrast, levels A and C document bifacial tools and the export of Levallois cores, which he interprets as indicators of logistical mobility. An independent study by Weiss et al. (2017) also demonstrated the technological conformity and similarities in raw material procurement patterns of the Königsaue assemblages, which were unrelated to the presence/absence of bifacial tools. Importantly, the assemblages from GK, while containing a few cortical pieces reflecting sparse primary reduction, lack bifacial technology, and demonstrate the export of Levallois flakes and the import of already prepared cores. As discussed above, we associated the assemblages as being the result of multiple, short-term occupations of the cave. The assemblages of Königsaue show general differences with GK in both core reduction (discoid methods) and tool assemblages (denticulates and "*Fäustel*"). Unlike at GK, Königsaue and the other sites mentioned above document the interstratification of bifacial and non-bifacial assemblages.

In many ways there are similarities between the assemblages from GK and Bosinski's (1967; quotation marks in original) "Moustérien" *Formengruppe* lacking bifacial technology, with Levallois modalities, mainly unifacial retouch and a predominance of scraper types. Bosinski included Balve IV (~60 ka), Buhlen II (see above) and Kartstein III (MIS 4-3) in this *Formengruppe*, or technocomplex. This category is reminiscent of Bordes' "Moustérien typique" (Bordes 1972) and similar to the Late (post-Eemian) Mousterian as described by Conard & Fischer (2000) as well as Richter's *Initialinventare* of the MMO in the "late Middle Paleolithic" (MIS 3 assemblages; Richter 2016), all of which lack bifacial artifacts. The assemblages at GK, however, differ from expected *Initialinventare* (see above) and are also unlike Balve IV and Buhlen II in not featuring retouched points and a laminar component (e.g. Bosinski 1967; Bosinski & Kulick 1973).

Finally, the Swabian Mousterian assemblages from GK contrast sharply with the somewhat older assemblages from MIS 5 in the Rhineland, like the hilltop volcanic crater of Tönchesberg (Conard 1992) and the floodplain deposits from Wallertheim (Conard & Adler 1997; Conard 2001; Adler et al. 2003). These sites, while also lacking bifacial elements, document greater technological diversity in terms of raw material procurement, more diverse patterns of lithic reduction and a more diverse tool spectrum than GK. In these open-air settings, the brief occupations reveal much higher technological variability and major short-term changes in knapping strategies and tool manufacture, use, recycling and discard compared to the case of GK and the other Swabian caves. The record from GK appears to reflect the presence of more stable behavioral adaptations and perhaps more stable populations than does the sample from the open-air sites in the Rhineland. Interestingly, the D-layers at Hummerich, another volcanic crater in the East Eifel (Bosinski et al. 1983, 1986; Street 2002), which post-date most of the find horizons at Tönchesberg except layer 1B and all of the six find horizons at Wallertheim, are of similar age to the lower deposits at GK, contain a record of bifacial and non-bifacial finds, underlining the diversity of these regional records. Unfortunately, the geological context of the MP from Hummerich is reworked and lacks the high chronostratigraphic resolution needed for more systematic comparisons.

In summary, GK differs most strongly from the comparative sites and other long sequences of the German MP in its consistent diachronic techno-typological signal within the time range of ~94-43 ka BP. The sequence is characterized by local raw material procurement, use of various modalities of Levallois in addition to Kostenki reduction, as well as bipolar and platform methods, abundant scraper forms plus splintered pieces and an absence of denticulates and bifacial implements. Despite the long timespan covered by the sequence, and in contrast to Sesselfelsgrotte, Buhlen, Königsaue, and other sites, the archaeological record at GK does not feature high intra-site variability with different technocomplexes, such as an interstratification of assemblages with and without bifacial pieces (e.g. MMO), and there is overall no evidence for bifacial flaking taking place at the site. Post-depositional and taphonomic arguments can be ruled out to explain the absence of these pieces – or their by-products – as modern field methods were used to excavate the site, allowing detailed geoarchaeological work and the recovery of artifacts regardless of their size. Based on these observations we conclude that the techno-typological signals at GK are distinctive from those of many other sites of similar age.

Implications for Neanderthal behavior, mobility patterns and demography

In combination with contextual information from geoarchaeology, zooarchaeology, absolute dating and field observations (Richter et al. 2000; Conard & Malina 2002, 2003; Münzel & Conard 2004; Conard & Bolus 2008; Conard et al. 2012, 2019; Higham et al. 2012, 2014; Richard et al. 2019), the MP lithic assemblages of GK offer insights on Neanderthal behavior, mobility patterns and demography in the Late Pleistocene of the Swabian Jura. Consideration of these findings contributes to our understanding of the lifeways of late Neanderthals as well as to the behavioral and demographic context of the late MP just before the arrival of modern humans in the region, which is documented at GK around 43 ka calBP (Higham et al. 2012).

In terms of raw material procurement and economy, the overall proportions of Jurassic chert at GK are even higher compared to many other MP sites within the region. This observation suggests a particularly strong focus on local raw material procurement from the close primary and secondary sources by Neanderthals. With regard to the overall structure of mobility, similar observation from other MP sites of the region suggest reduced spheres of residential and logistical mobility. Neanderthals likely spent most of the year in the region and usually organized their economic and social lives on a local scale but with high residential mobility (Conard et al. 2006, 2012).

As far as transport of raw material is concerned, the initial phases of decortification took place outside of GK, with cortex values being low on both blanks and cores. Knappers imported mostly prepared cores of Jurassic chert as well as finished pieces for other raw materials. Production and modification of blanks on Jurassic chert was a focus during the occupation at the site as is indicated by relatively complete reduction sequences and some small debitage, including occasional retouch flakes. The rarity of end products, particularly from Levallois reduction, suggests the export of selected blanks and tools from the site and could be viewed as an indicator of short-term use of the site. In sum, the low density of lithic artifacts and other anthropogenic materials in all the MP find horizons at GK in combination with a somehow fragmented reduction chain with common import and export of finds reflect a settlement system with high mobility and frequent movement of individuals and groups.

The low density of cultural materials also helps to shape our interpretations of the settlement dynamics of the Swabian MP in general and at GK in particular. At GK, the archaeological material does not originate from clearly defined find horizons (Fig. 4), and no coherent archaeological features could be identified during excavation or during subsequent analyses. This is also the case during the MP at Hohle Fels (e.g. Conard & Malina 2013) but contrasts markedly with the overlying Aurignacian at both these sites (Conard & Malina 2002, 2003; Conard et al. 2006, 2012). These stratigraphic observations are likely explained by taphonomic alteration and mixing of the MP layers by geogenic, biogenic and cultural processes, although the ephemeral and infrequent use of the site by Neanderthals points to a key role by other taphonomic agents (Conard 2011; Conard et al. 2012, 2019; Miller 2015). There is also the possibility that the excavations uncovered only the edges of the MP occupation centers (Münzel 2019). Moreover, frequent evidence for cryoturbation of the sediments damaging both bones (56 %; Münzel & Conard 2004) and lithic artifacts (67-71 %) is present throughout the entire MP sequence, but particularly in the uppermost layers IV and V, which also harbor a high amount of limestone debris reflecting higher geogenic input (see also Hahn 1988: 102-103; Conard & Malina 2002, 2003).

Analyses of faunal material found similar evidence for more abundant non-anthropogenic input, particularly from cave bears, higher levels of hominin mobility and lower population density for the MP compared to the UP at GK, as well as for Hohle Fels, Sirgenstein, Große Grotte, and Kogelstein (Münzel & Conard 2004; Conard et al. 2012; Kitagawa et al. 2012; Münzel 2019). In sum, several lines of evidence indicate repeated, brief knapping episodes during Neanderthal occupations of GK within a relatively long period (~94-43 ka BP). Prolonged periods of abandonment and use of the site by cave bears resulted in the accumulation of small lithic assemblages without recognizable archaeological features. Burnt bone varies between 8-24 g/m^3 in the MP layers at GK (Conard et al. 2012). The material almost certainly results from the controlled use of fire by Neanderthals inside the cave, but taphonomic processes, including most notably actions of cave bears, have damaged the context of the burnt faunal remains recovered during the excavation and subsequent analyses. Although there are rare cutmarks on MP faunal remains and rare anatomical refits, there are no cutmarks on the burnt bones (Münzel 2019). As is usually the case for fragments of burnt bone, the bones cannot be identified to species level. Diverse biological activities including denning and hibernation by bears can radically effect the preservation of Paleolithic sites (Fosse et al. 2004; Camáros et al. 2016), and the well documented and intense use of GK and many other Swabian caves by cave bears underline their importance in modifying the archaeological record of the MP.

The consistent signal of low-density archaeological material at GK and other sites of the Swabian Jura generally suggests low intensity occupation of caves and high residential mobility by Neanderthals during the Middle Würmian. Most known open-air sites derive from surface collections, such as Wippingen, Sonderbuch or Asch, and have yielded comparatively low find densities of unequivocal MP artifacts such as isolated *Keilmesser* (Floss & Schürch 2015). Richer sites including Börslingen or Wittlingen (Burkert et al. 1992; Floss et al. 2012) are likely quarry sites, hindering direct comparisons. While it is difficult to relate these observations directly to measures of demography, low populations combined with higher residential mobility in the Swabian Jura seem the most likely explanation. Additional evidence for such demographic interpretations comes from recent paleogenomic studies from the Neanderthal femur of Hohlenstein-Stadel (Posth et al. 2017), but also from genetic analyses of other Neanderthal remains in Eurasia (e.g. Castellano et al. 2014; Prüfer et al. 2014), finding evidence for inbreeding alongside low genetic diversity.

Several studies using archaeological proxies for estimating demographic parameters have found a population increase following the shift from the MP to the UP (Bocquet-Appel & Demars 2000; Conard et al. 2006, 2012; Mellars & French 2011; Bocquet-Appel & Degioanni 2013), but such studies face several methodical problems (e.g. Dogandžić & McPherron 2013; more generally Bocquet-Appel 2008; French 2015). It is also relevant to note that not all MP sites from the Swabian Jura are archaeological deposits with small assemblages and low densities, such as is the case at Bockstein and Heidenschmiede (Peters 1931; Wetzel & Bosinski 1969; Çep 2014; Çep & Krönneck 2015), indicating either longer occupations, larger groups using the sites or slower rates of geological deposition when the MP find horizons formed. Many European localities from neighboring regions during similar temporal frames including Sesselfelsgrotte (Weißmüller 1995; Richter 1997) and Buhlen (Bosinski & Kulick 1973; Jöris 2001; Fiedler 2009) in Germany or further into the west at the Vanne-Tal in France (Depaepe 2007), to the east at Kůlna 7a (Valoch 1988; Neruda 2017), or to the south at Fumane (e.g. Peresani et al. 2011) exhibit higher artifact densities and reflect higher occupation intensities than do the find horizons at GK.

Radiometric dates for the MP at GK of ca. 94-43 ka BP (Richter et al. 2000; Higham et al. 2012, 2014; Richard 2015; Richard et al. 2019) provide an important chronological anchor for the region, since reliable dates are lacking for most other sites in the Swabian Jura. With the upper portion of the MP assemblages of GK dating to ~50-45 ka BP, our results provide insights into the behavior and demography of late Neanderthals living in southwestern Germany prior to the arrival of anatomically modern humans. Differences in the use of the site and potentially population density are most striking when comparing the MP of GK directly with the overlying Aurignacian. After a short occupational hiatus, the Aurignacian at the site is characterized by different faunal assemblages, new technologies and novel lithic and organic artifacts, including a great variety of personal ornaments, figurative art objects and musical instruments, all unknown in the preceding MP (Hahn 1988; Conard & Bolus 2003, 2006, 2008; Münzel & Conard 2004; Conard et al. 2006, 2015). The clear stratigraphic and behavioral discontinuity between the uppermost MP layers and the Aurignacian horizons at GK is further substantiated by a sharp rise in find densities for all classes of archaeological materials at the base of the Aurignacian and no mixing between the archaeological horizons. The end of the MP and the subsequent occupational hiatus at GK and many other sites in the Swabian Jura (Conard et al. 2006) points to a decrease in occupation intensity associated with a dwindling population of Neanderthals. The gap between Neanderthal and modern human occupations at GK and other sites suggests that the former might have abandoned the region, with UP groups expanding into largely depopulated territory as postulated by the 'Population Vacuum' hypothesis (Conard 2003; Conard et al. 2003b; Conard & Bolus 2006). In addition, Neanderthal occupations of the cave sites of the Swabian Jura with small lithic assemblages and relatively low amounts of other anthropogenic materials reflect more short-term stays within a system of higher mobility compared to modern humans in the Aurignacian of the area.

The break in archaeological and demographic signatures between Neanderthals and *Homo sapiens* found at GK is similar to the record in southern and west-central German record of the late MP (Richter, 2016; Uthmeier 2004; Böhner 2008). This pattern stands in marked contrast with other European regions (Bolus 2004a; Peresani et al. 2008; Soressi et al. 2013; Higham et al. 2014), as is exemplified by technocomplexes such as the Chatelperronian (e.g. Harrold 2000; Soressi & Roussel 2014), Uluzzian (Palma di Cesnola 1989; Peresani et al. 2008), and Szeletian (Allsworth-Jones 1986; Skrdla et al. 2014; Hauck et al. 2016). While there is heated debate on the purported transitional nature, stratigraphic integrity and makers of these entities (e.g. Higham et al. 2010; Benazzi et al. 2011; Soressi & Roussel 2014; Zilhão et al. 2015; Gravina et al. 2018), neither the Swabian Jura nor southern and west-central Germany (Richter, 2016; Uthmeier 2004; Böhner 2008) feature transitional cultural stratigraphic entities beyond the *Blattspitzengruppe*, which is usually viewed as a cultural development arising from the late MP independent of contacts with modern humans.

Instead, southwestern Germany is home to a late MP with more typical features as reflected in the Swabian Mousterian. The UP follows without recognizable interaction in the form of a very early but fully developed Aurignacian characterized by a vast range of cultural innovations lacking in the region's MP. While the basic structure of the Swabian record is clear, and highlights the varied spatial nature of the European Paleolithic record, explaining these regional differences and gaining a better grasp of the chrono-cultural stratigraphy of the late MP of the Swabian Jura remain essential lines of future inquiry. The ongoing excavations into the stratified MP layers of Hohle Fels (e.g. Conard & Janas 2018) will provide such an opportunity for testing and refining results from GK presented here.

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Inhalt - *Contents*