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The Variability of the *Keilmesser-Concept*: a Case Study from Central Germany

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Abstract

The bifacial Keilmesser is the type fossil of the late Middle Paleolithic *Keilmessergruppen* or *Micoquian* of central and eastern Europe. The tool is variable in shape but standardized regarding shaping sequences and morphological components. In this study we examine whether these components, a base and back opposite a sharp edge, are related only to bifacial tools or if they form a functional tool concept that was applied as well to simple edge retouched and to unifacially shaped flake tools. This study is based on a dataset of 29 3D-scanned artifacts from central Germany, for which the geographic origin, paleoenvironment, and chronological context are known in order to reduce variability introduced by these factors. With new luminescence dates, we can provide a chronological time frame for the collected and excavated artifacts to between 55 and 40 ka. We analyze variability caused by function, blank type, shaping, intensity of retouch, and typology, using 3D geometric morphometrics, Thickness Mapping, edge angle analysis, and multivariate principal component analysis based on conventional technological attributes and indices. We show that the unifacially shaped scrapers with a Keilmesser-like morphology can be classified as a unifacial variant of the bifacial Keilmesser. We interpret simple scrapers with a Keilmesser-like morphology as a special, simplistic variant of Keilmesser where the blank already fulfills the functional requirements of prehensile and active parts. With some caution related to sample size, an additional sample of Micoquian handaxes appears to be a related, but more symmetric tool concept in our data set.

Keywords Keilmesser · Keilmessergruppen · Micoquian · 3D geometric morphometrics · Principal component analysis · Thickness Mapping

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Introduction

The late Middle Paleolithic with bifacial tools that is characteristic of central and eastern Europe is classified as *Micoquian* (Bosinski 1967; Günther 1964; Kozłowski 2014) or *Keilmessergruppen* (Jöris 2004; Mania 1990, 2002; Veil et al. 1994). The common denominator or type fossil of these assemblages is the asymmetric bifacial backed knife or *Keilmesser* (hereafter: Keilmesser), which is defined by a natural and/or retouched back opposite a bifacially retouched cutting edge, often having a pronounced tip opposite a thick base (Bosinski 1967; Chmielewski 1969; Jöris 2001, 2006, 2012; Koulakoskaya et al. 1993; Krukowski 1939–1948). The occurrence of the plano-convex shaped Keilmesser (e.g., Jöris 2001, 2006, 2012) in late Middle Paleolithic assemblages is seen to separate the Keilmessergruppen or the Micoquian (we will use these terms synonymously) of central and eastern Europe from the contemporaneous *Mousterian of Acheulian Tradition* (hereafter: MTA) of western Europe (Ruebens 2012, 2013, 2014; Soressi 2002). Typical for the latter are biconvex handaxes with two cutting edges converging at a distal tip (e.g., Soressi 2002). Besides the Keilmesser, Micoquian assemblages have leaf-shaped bifacial tools, like leaf-shaped scrapers and *Faustkeilblätter*, bifacial scrapers, bifacial points, handaxes, and various forms of scrapers (e.g., Bosinski 1967; Richter 1997; Ruebens 2012, 2014).

During the study of the late Middle Paleolithic stone artifact assemblage from the Pouch-Terrassenpfeiler site (hereafter: Pouch), located near Bitterfeld, Saxony-Anhalt/Germany (Weiss 2015), it was noticed (Fig. 1) that the morphological components or techno-functional units defined for the bifacial Keilmesser (see below) are found as well on one-sided shaped tools ("unifacially shaped tools") and on simple edge retouched scrapers ("simple scrapers"). Similar simple scrapers and unifacially shaped tools with a Keilmesser-like morphology occur in other Keilmessergruppen assemblages from central Germany. Examples are Salzgitter-Lebenstedt, Lower Saxony/Germany (e.g., Pastoors 2001: "Werkzeuggestalt 12"), Lichtenberg, Lower Saxony/Germany (e.g., Veil et al. 1994: Fig. 25,4) and layers A and C from Königsaue, Saxony-Anhalt/Germany (e.g., Mania and Toepfer 1973: Plates 30,2; 30,3; 32,7; 64,1; 64,2). That these simple edge retouched, unifacially shaped and bifacial late Middle Paleolithic tool forms might be related was already suggested some 80 years ago when Krukowski defined the term "Prądnik cycle" (Krukowski 1939–1948) to express the idea of a dynamic continuum from simple edge retouched and unifacially shaped knives ("Prądnikshaks") to bifacial tools and remnant pieces. A functional relationship between some scrapers and Keilmesser was suggested as well by some of the techno-functional tool categories established by Pastoors (2001) for the assemblage of Salzgitter-Lebenstedt. In his definition of the Keilmesser, Jöris (Jöris 2012, p. 301) states as well that some Keilmesser may be represented by "more or less" shaped asymmetric flake tools, with a sharp edge opposing a blunted edge (see also Jöris 2006). Furthermore, Veil et al. (1994) suggest a functional relationship between the standardized convex cutting edges of scrapers and bifacial tools for the assemblage of Lichtenberg (for similar observations regarding late Middle Paleolithic cutting edges, see Boëda 1995).

A few late Middle Paleolithic handaxes (hereafter: "Micoquian handaxes") were identified within the collected assemblages from around the site of Pouch. While interpreted as different from Keilmesser (Veil 1995; Veil et al. 1994) in having a more symmetric tip and a longer and sharper edge between back and tip ("distal posterior part," see below), the Micoquian handaxes in our dataset seem to share generally the basic morphological features of bifacial knives as well. It was already suggested that Middle Paleolithic Keilmesser are a special variant of handaxes (Hahn 1990) with only one cutting edge opposite a back. This relationship was questioned by some (Jöris 2012; Veil et al. 1994) for the late Middle Paleolithic where the two tool classes are interpreted as highly standardized regarding their reduction sequences and morphological components and hence different from each other. However, a recent morphometric study (Serwatka 2015) comparing 2D shapes of handaxes, Keilmesser and leaf points using Elliptical Fourier Analysis (Serwatka 2015) revitalized the idea of a strong relationship, as the outline shape of Micoquian handaxes falls within the variability of Keilmesser.

To understand the functional and technological/morphological concept of the bifacial Keilmesser and how it has been defined, certain terms for morphological components (e.g., Jöris 2001, 2006, 2012) like "back," "base," or "working edge" suggest that specific areas or zones of the tool can be differentiated based on a concept of techno-functional units (Boëda 1997, 2001; Lepot 1993). In this approach a tool is divided into three components: a prehensile part, a receptive part that receives the energy and transmits it through the stone tool, and a transformative part, which transfers the energy to the worked material (e.g., cutting edge). Following Boëda (2001), the receptive/transmitting component of bifaces does not form a separate zone and is already integrated into the prehensile and the transformative functional units. In this approach, morphology and shaping are driven by functional requirements. The main goal of bifacial shaping is then to create a prehensile and a transformative part (Boëda 2001) on a tool. In subsequent studies of western European MTA handaxes, the analysis of these functional areas was combined with use-wear studies (e.g., Claud 2012; Soressi and Hays 2003) to trace active and prehensile zones on these stone tools (Soressi 2002).

This approach of relating function with morphology and shaping has been adapted as well to late Middle Paleolithic in central and eastern Europe with a special focus on the bifacial Keilmesser (e.g., Iovita 2009, 2010, 2014; Jöris 2001; Pastoors 2001; Richter 1997; Veil et al. 1994). Some researchers (e.g., Pastoors 2001; Richter 1997) combined the analysis of the positions and morphologies of functional edges on the tools with an analysis of tool biographies ("Arbeitsschrittanalyse") to create techno-functional tool categories. In this approach, types like Keilmesser were "dissolved" and assigned to new groups based on the morphology and position of their edges and their shaping sequences (Pastoors 2001). This led to categories that included scrapers, bifacial scarpers, and Keilmesser (e.g., "Werkzeuggestalt 12", Pastoors 2001: pp. 154–155).

On the other hand, Jöris (2001, 2004, 2006, 2012), but also Richter (1997), interpreted similarities of shaping sequences and techniques to create a standardized morphological and functional concept of the Keilmesser. Following these interpretations, this bifacial tool has an asymmetric cross-section with the back being the thickest part, and it is worked in a plano-convex manner, with one surface being more convex than the other. Although Keilmesser morphology is variable and sub-types can merge into one another (e.g., Jöris 2006, Fig. 7), certain components are typical for this bifacial tool type (e.g., Jöris 2004, 2006): a thick base, a sharp edge or cutting edge opposite a natural and/or retouched back, and a distal posterior part adjacent to the back and converging with the cutting edge to a more or less pronounced tip. The distal posterior part is mostly sharp towards the tip, but it can also be partly blunted and served as striking platform for shaping (see e.g., Fig. 1 and Fig. 4(1)). The back of Keilmesser is interpreted as the prehensile part of the tool where no hafting was required. Functionally, based on their standardized cutting edge with angles < 60° and based on use-wear traces, Keilmesser are interpreted as cutting tools (Jöris 2006, 2012; Richter 1997; Veil et al. 1994).

The stability of certain morpho-functional parts and the stability of the overall shape during the life history of a Paleolithic stone tool has been examined in many resharpening

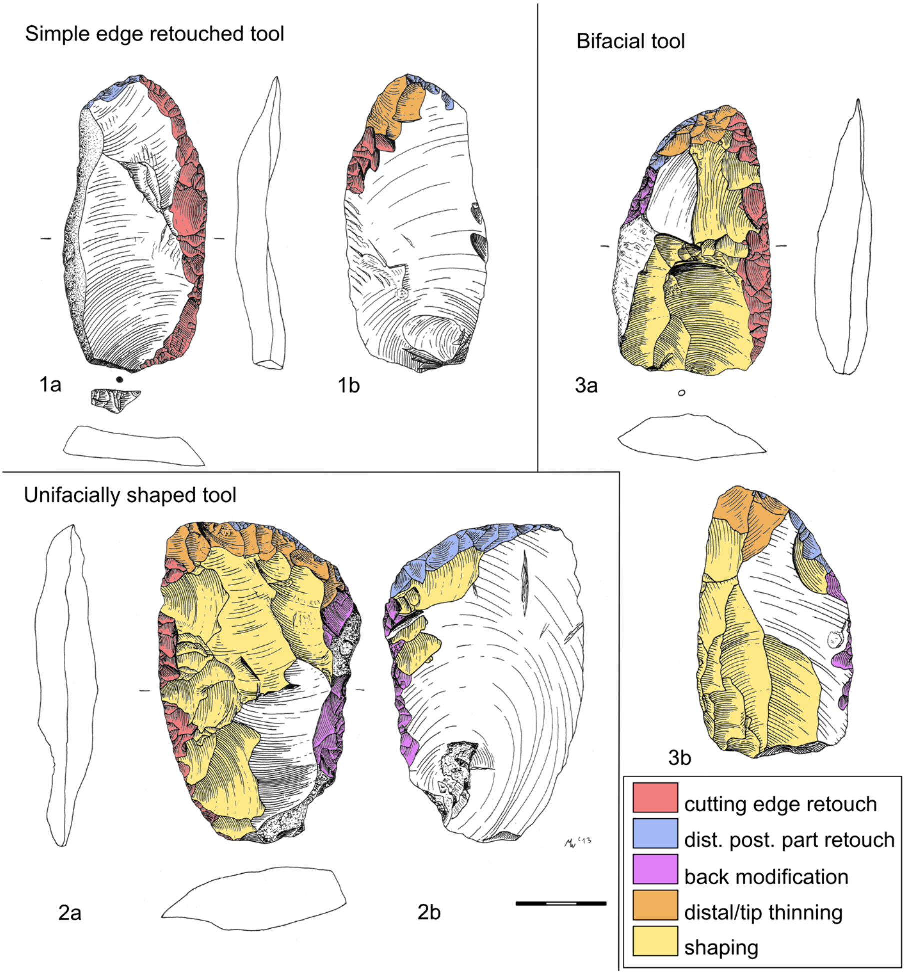

Fig. 1 The transformation from simple edge retouched to unifacially shaped and bifacial tools ("Prądnik cycle") as suggested by the interpretation by Weiss (2015), demonstrated on examples from Pouch. The subsequent transformation might be due to further reduction and resharpening. Highlighted are comparable edge and surface modifications characteristic for the components of bifacial Keilmesser. Simple edge retouched scrapers ("simple scrapers") only lack shaping (unifacial and bifacial). (1) Simple scraper with Keilmesser-like morphology and ventral retouch, Pouch (2004:8679,19); (2) unifacially shaped scraper Pouch (2004:8679,5); (3) Keilmesser made on flake, Pouch (2004:8679,2). Drawings: M. Weiss

studies (e.g., Boëda 1995; Dibble 1987, 1995, Iovita 2010, 2014; Iovita and McPherron 2011; Jöris 2001; McPherron 1995; Migal and Urbanowski 2006; Morales et al. 2015b; Morales 2016; Urbanowski 2003). Iovita (2009, 2010, 2014) understands resharpening as a repetitive process that creates patterns that affect tool shape variation in relation to size. He interprets resharpening patterns as an “index of function” (Iovita 2009, p. 1447). In other words, if individual edges or components of typologically distinct tools are reduced in a similar way, comparable functions can be inferred. Thereby, reduction is divided into “isometric” and “allometric” types (e.g., Iovita 2010; Morales et al. 2015b). Isometric reduction is shape-conserving (Iovita 2010; Morales et al. 2015b), i.e., that shape is retained during the resharpening process. During the allometric resharpening, the shape of the tool is altered during the reduction process. Here, the maintenance of the working edge itself and not the overall tool morphology seems to be the most important aspect of the tool, as it has been shown for the variability of Middle Paleolithic scraper morphologies (see Dibble 1987, 1995). Isometric reduction, instead, implies that a certain morphology of a tool is linked to specific tasks and that its shape is important enough that it must be maintained during resharpening of the tool.

For the bifacial Keilmesser from Buhlen, Hesse/Germany, a tendency towards an allometric shape change from elongated to more rounded outline shapes was shown recently (Iovita 2010; see also Jöris 2001, 2004, 2012; Migal and Urbanowski 2006; Urbanowski 2003). However, the allometric relationship between shape and size is rather weak in Buhlen (Iovita 2010), and during reduction the asymmetric length relationship between the individual edges is retained. In other words, whereas the overall tool shape undergoes a slight allometric shape change during reduction, the morphological/functional units of Keilmesser themselves are isometrically reduced and the relationship between them stays constant in Buhlen independent of size. This implies that the morpho-functional components of this tool type are either culturally distinct in that this tool defines the Keilmessergruppen (e.g., Jöris 2001, 2004, 2006, 2012; Mania 1990; Ruebens 2012, 2014; Veil et al. 1994), and/or linked to certain reduction and resharpening strategies (e.g., Iovita 2014; Jöris 2001), and/or functionally important to perform a certain tasks (e.g., Jöris 2006, 2012; Richter 1997; Veil et al. 1994), but for discussion see Rots (2009).

Summarizing from what was outlined above, similar function may be indicated by a comparable distribution of active and prehensile parts (e.g., Boëda 1997, 2001; Claud 2012; Lepot 1993; Soressi 2002; Soressi and Hays 2003) that were modified and potentially further resharpened in a comparable way (Iovita 2009, 2010, 2014). Applying this approach to Keilmesser, unifacially shaped and simple edge retouched scrapers with a Keilmesser-like morphology as well as the handaxes in our dataset, similarities in functionality would indicate that they are based on a single tool concept.

Therefore, the aim of the present study is to analyze typologically distinct tools that have comparable morphologies to demonstrate in a quantitative way how variability is structured within and between the selected tool groups and to see, therefore, whether we can demonstrate a comparable functionality. More specifically, this study seeks to ascertain the nature of the functional and morphological relationship between (a) Keilmesser-like tools (simple edge retouched, unifacially shaped, and bifacial) and (b) Keilmesser and handaxes while controlling for the geographic origin, paleoenvironment, and age of the samples. For the latter, we evaluate and reinforce the existing chronology for the assemblages with new luminescence dates.

To test our assumption, we analyze variation in 3D edge shape, thickness distribution, edge angles, and technological variables that could be driven by functional differences or similarities. In addition, we evaluate what influence factors like blank type, shaping, retouch and classification or typology have on variability in the tools in question. To analyze these different aspects of variability, we used the combination of the following quantitative analytical methods: (1) the analysis of the 3D outline shape using 3D geometric morphometric (hereafter: 3DGM), we (2) mapped the thickness based on the 3D models to analyze the thickness distribution, we (3) computed and analyzed the edge angles along the active edges based on the thickness maps, and we (4) analyzed the distinct tool types with regard to conventional attributes like the minimum and maximum edge angles of the working edge, intensity of retouch, flatness, and elongation.

To enlarge the dataset and to not only rely on the artifacts from the assemblage of Pouch, we added additional tools from collected assemblages (Goitzsche and Löbnitz, see materials section) from the vicinity of the site, coming from the same geological and chronological context. To this end we focus on a regional dataset of 29 3D scans of Keilmesser, Micoquian handaxes, and unifacially shaped and simple edge retouched scrapers with Keilmesser-like morphology. As a small sample size was unavoidable using this approach (see section "Lithic Analysis"), an additional dataset of 163 tools with attribute data coming from the same assemblages was included to analyze the tools in question in a broader context of late Middle Paleolithic tool types. Whereas our main focus lies with Keilmesser-like tools, the Micoquian handaxes were added to this study as their main difference to Keilmesser seems to be the length and sharpness of the distal posterior part or second cutting edge (Veil 1995; Veil et al. 1994). Although the sample size with regard to the diversity of late Middle Paleolithic handaxes (e.g., Bordes 1961; Bosinski 1967; Debénath and Dibble 1994) is small, we included the four handaxes within our study to have an idea of whether there might be some relationship between Micoquian handaxes and Keilmesser.

The work presented here is a first attempt to apply a more objective and quantitative set of analytical methods to analyze bifacial Keilmesser morphology. Our aim is to introduce a novel, more quantitative way of studying stone tools that goes beyond description, typology, and conventional measurements (see e.g., methodology in Ruebens 2012). Therefore, we use an example of late Middle Paleolithic tools to compare tool categories that might be obviously similar in shape and perhaps function but distinct regarding typological criteria, for example the presence or absence of bifacial retouch, blank type, and symmetry. In consequence, this approach may help us to understand better the variability within the late Middle Paleolithic stone tool record and how valid our typological descriptive criteria are for understanding late Neanderthal tool manufacture and tool use.

Materials

Regional Geology, General Site Characteristics, and Existing Chronology

Geology

The study area is located about 25 km north of Leipzig (Fig. 2) and belongs to the Leipzig Basin ("Leipziger Tieflandsbucht") which is part of the northern German Lowlands.

The geological basement of this area is built by metamorphic and igneous rocks of the Variscian Orogenesis (Eißmann 2008) overlain by unconsolidated Tertiary and Quaternary sediments. During the Middle Pleistocene, Scandinavian ice-sheets covered this area three times. The Elsterian and Saalian glaciers significantly reorganized the palaeo-geomorphology of the area, for example, forcing a deviation of the main river systems and creating subglacial valleys that were later filled again with unconsolidated sediments (Eissmann 2002). During the last glacial period, a periglacial environment including various fluvial aggradation periods characterized the area (Mol 1997), and eolian deposits overly fluvial sands and gravels but only a thin sandy loess cover is preserved in some areas.

The analyzed artifacts derive from the base of the last glacial fluvial sand and gravel deposits (the "Lower Terrace") of the river Mulde, which is a tributary of the Elbe River. The Weichselian fluvial sedimentary sequence in the area is around 11 m thick, and the sedimentary architecture of the fluvial succession includes coarse gravel layers, intercalated by partly cross-bedded sand layers pointing to a braided river system at time of fluvial aggradation. Ice wedges and cryoturbation features also point to cold climatic conditions (Fig. 3) during and after the aggradation of the different units. For central and western European river systems, various periods of fluvial aggradation and

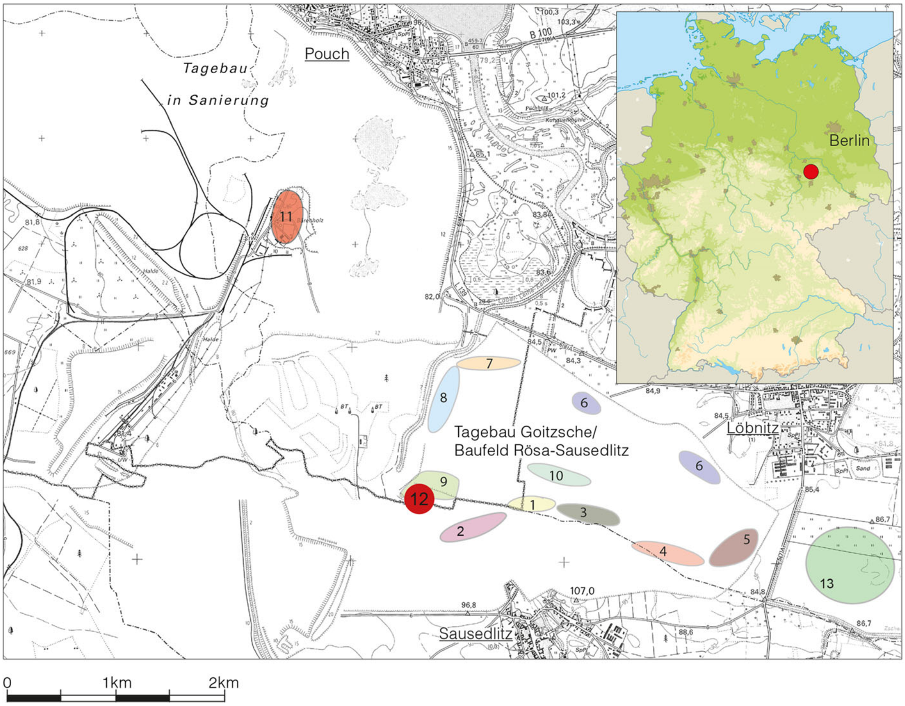

Fig. 2 Map of the find spots in the former brown coal quarry "Tagebau Goitzsche" east of Bitterfeld and the gravel pit of Löbnitz. The tools analyzed in this study come from the excavated site of Pouch-Terrassenpfeiler (12), surface collections of the southern slope of the former brown coal quarry "Goitzsche" north of Sausedlitz (1–3), and the gravel pit of Löbnitz (13). The sites (1)–(6), (10), and (13) belong to the federal state of Saxony and the assemblages (7)–(8) and (11)–(12) to Saxony-Anhalt. For detailed site names and analysis of the assemblages, see Weiss (2015). Graphic: M. Weiss/MPI-EVA; (Weiss 2015)

sedimentary deposition were recently demonstrated based on luminescence dating spanning from the early Weichselian (e.g., Cordier et al. 2014; Kolb et al. 2016; Lauer et al. 2010) to the late Weichselian (Lauer et al. 2011). Fluvial activity in the study area during the Weichselian glacial cycle was mainly triggered by climatic shifts regulating fluvial aggradation and erosion cycles (see also Mol 1995, 1997).

General Assemblage Characteristics

The site of Pouch was partly excavated (2 m^2) in 2002 until a flood of the river Mulde raised the level of the growing lake within the abandoned quarry and made the site no longer accessible. The site was situated within the former open-cast brown coal mine Goitzsche (Fig. 2), at the base of the gravel, sand, and silt sequence of the last glacial terrace (hereafter: Lower Terrace) of the river Mulde. The gravels at the base of the sequence are rather large and yielded large and high quality flint nodules as raw material for stone tool manufacture. The 371 artifacts were excavated from two find concentrations with a single find layer in each concentration (Weiss 2015). Thereby, 96 artifacts come from the main and 20 artifacts from a smaller concentration. Two hundred fifty-five artifacts were recovered from the exposed profile prior to the rescue excavation by volunteer archaeologists who secured the material from wave erosion of the expanding lake. Regarding the documentation and the recorded vertical position of the artifacts (Seiler and Runck 2003; Weiss 2015), they belonged to the main find concentration as well. That the artifacts presumably represent one assemblage is evidenced by comparable sediments of the find bearing layers, as well as some identical raw material units and seven refit complexes (Weiss 2015) that included also pieces from the rescue works prior to the excavation. Prepared core techniques including Levallois methods are present in the assemblage, and the 58 complete tools consist of two bifacial or leaf-shaped scrapers, three Keilmesser as well as backed scrapers and other formal tools (Weiss 2015). Therefore, the assemblage can be attributed to the late Middle Paleolithic Micoquian or Keilmessergruppen.

Artifacts from the former brown coal quarry “Tagebau Goitzsche–Baufeld Rösa-Sausedlitz” were collected between 1991 and 2002 by volunteer archaeologists and geologists during reconstruction works and refilling of the abandoned pit with water. The artifacts were recovered from several find horizons within the lowermost 6 m of the base of the gravel accumulations of the Lower Terrace sequence. Almost half of the artifacts show sharp edges (Weiss 2015), suggesting limited movement. On the base of tool typology (see e.g., Table 2), like the presence of Keilmesser, handaxes, bifacial and leaf-shaped scrapers (Ruebens 2012, 2013, 2014) as well as the blank production methods, like Levallois, prepared and non-prepared cores, the collection of 1008 complete artifacts can generally be attributed to the late Middle Paleolithic Micoquian of eastern and central Europe.

The ongoing gravel pit of Löbnitz is directly east of the former brown coal quarry of Goitzsche in the quarry field “Rösa-Sausedlitz” (Fig. 2). Here the gravels of the Lower Terrace sequence are exploited by a floating dredger. The gravel is then separated into different size fractions and the coarse gravel is dumped on a separate pile. Volunteer archaeologists and geologists have collected more than 3000 complete and damaged stone artifacts since the 1990s (Rudolph et al. 2003), which are now stored in the collection of the Archaeological Heritage Office Saxony in Dresden. Together with characteristic Levallois and prepared core flake production, Keilmesser, leaf-shaped, and bifacial scrapers as well as handaxes (see e.g., Table 2), the collection can be generally attributed to the late Middle Paleolithic of central and eastern Europe (see Supplementary Information). There was no other gravel accumulation in this area. Thus, we can infer that the artifacts collected in the gravel pit of Löbnitz originate roughly from the same chronological and geological context as the stone artifacts from the Goitzsche collection and from Pouch.

Chronology

Currently available chronological data from Pouch-Terrassenpfeiler (Weiss 2015) and around the site show the preservation of fluvial sediments in a time frame spanning from around 60 to 25 ka. Sediment from the upper "Löbnitzer Horizont" (Fig. 3) was radiocarbon dated to between ~38,000 and ~26,500 calBP (1σ) and the lower "Löbnitzer Horizont" to between ~40,000 and ~31,000 calBP (1σ) (Hiller et al. 1991; Weiss 2015). For the base of the Lower Terrace, some OSL and radiocarbon dates are available from the site of Pouch (Weiss 2015). Two OSL ages for a silt lens about 0.5 m above the base of the Lower Terrace are 56.5 ± 4.4 and 56.2 ± 5.1 ka. The find layer for the late Middle Paleolithic artifacts, about 1 m above the base of the sequence, yielded OSL ages of 47.1 ± 2.7 and 46.2 ± 2.5 ka. Besides some younger radiocarbon ages on sediment for the find layer of about 30,000 calBP, which were potentially contaminated with younger humic acids, two radiocarbon dates of 46,000 to ~43,000 cal BP (1σ) and 43,000 to ~41,000 calBP (1σ) for the find layer are in accordance with the luminescence ages. The radiocarbon ages presented here were calibrated with OxCal, IntCal 13. For a detailed discussion of the numerical ages, the lab codes, uncalibrated dates, standard errors, as well as information about the dated material, the reader is referred to the original publications (Hiller et al. 1991; Weiss 2015).

Luminescence Samples

The luminescence samples were collected by M. Krbetschek in June 1999 along the northern slope of the mine at a time when the former open-cast brown coal mine was still accessible. Unfortunately, M. Krbetschek passed away before he was able to date the samples. These luminescence samples were recently provided to us by the Freiberg (Saxony/Germany) dating laboratory.

Sample Ros-1 comes from sandy gravels, about 15 cm above the artifact bearing base of the lower coarse unit (Fig. 3). The second sample, Ros-2, was collected in the middle part of the Lower Terrace sequence, about 4 to 5 m above the base (Fig. 3). The last sample, Ros-3, was collected at the top of the sequence. The sample was recovered about 60 to 70 cm below the top of the gravel succession and 1.5 m below the present-day surface (Fig. 3). Originating from the base, the middle, and the top of the sequence, the three samples encompass the entire period of fluvial aggradation. As the archaeological finds come from the basal layers of the sequence, Ros-1 from the base represents a minimum and Ros-2 a maximum age for the artifacts.

Lithic Analysis

Artifact Types Analyzed with 3DGM and Thickness Mapping

In the morphometric analysis part of the present study, we include Keilmesser, simple edge retouched and unifacially shaped scrapers with a Keilmesser-like morphology, as well as handaxes from Pouch and from the Goitzsche and Löbnitz collections (Table 1).

The *sample size* (29 pieces) is small due to some general aspects of this study: (1) We control for the region, as all the stone tools come from an area within a few square

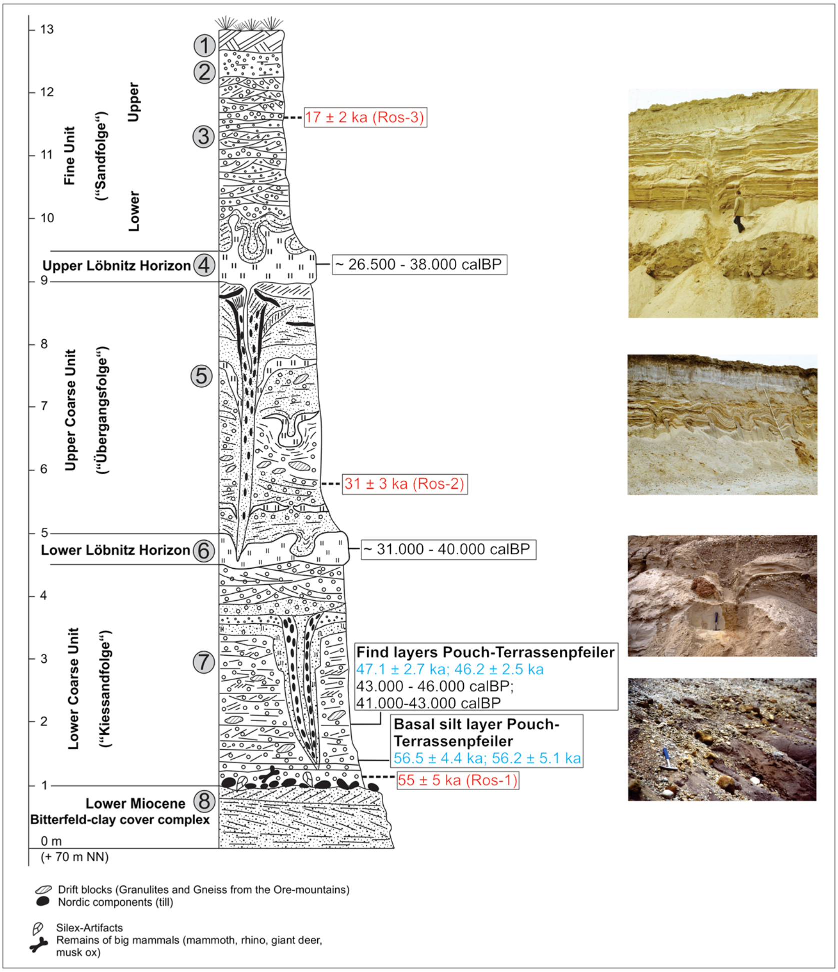

Fig. 3 Schematic profile of the Lower Terrace Sequence. (1) Top soil; (2) cover sand overlying fluvial sand and gravel; (3) partly cross-bedded sand and gravel; (4) organic rich silt/ fine-sand/ clay; (5) mostly horizontally layered fluvial sand and gravel + strong cryoturbation features; (6) silt-rich peat; (7) gravel dominated deposits including Nordic rock components/ blocks, ice wedges; (8) Tertiary sand. Dates in black, calibrated radiocarbon ages, 1σ error range (OxCal, IntCal 13); blue, luminescence ages; red, new luminescence ages presented in this study. Dates on Pouch-Terrassenpfeiler, see Weiss (2015); radiocarbon ages for the “Löbnitzer Horizonte,” see Hiller et al. (1991) and Weiss (2015). Graphic: R. Wimmer and I. Heibert

kilometers. This area was specifically chosen, because the previous analysis of the site Pouch (Weiss 2015) revealed a potential relationship between bifacial, simple edge retouched and unifacially shaped tools concerning their “Keilmesser-like morphology.” (2) We like to control for the general chronological attribution, as all the tools, including the excavated assemblage, come from the same geological-chronological context, namely the base of the early MIS 3 Weichselian Lower Terrace. (3) All sites were located on a river bank with access to large, high quality and flint nodules. Therefore, we can infer that the tools were produced and used under the same environmental conditions. Another fact that restricts sample size (4) is that Keilmesser and handaxes, as well as scrapers that show Keilmesser-like morphology, are rather rare compared to flakes, cores, and other formal tools within these assemblages. Further, simple scrapers and unifacial shaped tools with backs (cortical, retouched, platforms) opposite a sharp and/or retouched edge are frequent in the assemblage of Pouch (Weiss 2015). For the purpose of this study, we specifically selected those retouched artifacts that replicate Keilmesser components. If any of these components is missing, the artifact was excluded from the analysis. Examples are tools that lack a retouched tip and/or a modified distal posterior part, or that have a base or a back that is not formed by parallel edges, allowing no placement of the specific landmarks. Therefore, there is a potential that more tools from Pouch mimic Keilmesser morphology without having additional modifications. Furthermore, some artifacts were currently not available for scanning, such as a number of pieces from Löbnitz which are on display at the Staatliches Museum für Archäologie, Chemnitz.

In this study, the sample size for Keilmesser is larger than for the other tool groups, and as a result we can expect a larger range in variability for this tool group. However, the purpose of this study is not to analyze variability in bifacial Keilmesser themselves, but rather to compare other tool groups to the range of morphological variation seen in Keilmesser. Because Keilmesser are regarded as a highly variable tool type regarding shape (e.g., Jöris 2006, 2012), a large sample size is required to document its variability and to see whether there is overlap with the other tool types.

Keilmesser (Fig. 4(1), Fig. 5(2), Fig. 6(2), Supplementary Information Figs. 1–6, 30, 37–38) or bifacial backed knives are defined by a bifacially retouched cutting edge opposite a naturally and/or retouched back, a thick, mostly unretouched proximal base opposing a distal, pronounced tip and a rather plano-convex, asymmetric (“wedge shaped”) cross-section (Bosinski 1967; Jöris 2001, 2006, 2012; Koulakoskaya et al. 1993). The back should cover at least one third of the edge opposite the cutting edge (Müller-Beck 1983). Jöris (2006) specifies four morphological parts (Fig. 4(1), see also

Table 1 The number of scanned artifacts

Site name	Keilmesser	Handaxe	Unifacially shaped scraper with Keilmesser-like morphology (K.-M.)	Simple scraper K.-M.	Total
Pouch	3	0	3	5	11
Goitzsche	2	1	1	0	4
Löbnitz	11	3	0	0	14
Total	16	4	4	5	29

Fig. 8a) of the tool: (1) the cutting edge, (2) the base, (3) the back, and (4) the distal posterior part between the back and the point of the tip. The distal posterior part is often blunted towards the back but sharp in the tip region (Veil et al. 1994). These morphological features are used in this study equally to describe the morphology of the other three tool categories (for handaxes see Fig. 5(1), Fig. 6(1)).

The *unifacially shaped and simple edge retouched scrapers* with Keilmesser-like morphologies (Fig. 4(2–3), Fig. 5(3), Fig. 8c–d, Supplementary Information Figs. 17–25, 30, 31–36) possess a natural and/or retouched back opposite a retouched cutting edge, a base (sometimes formed by the platform), and a thinned and/or pronounced tip. In other words, they possess all the relevant components, i.e., base, back, modified distal posterior part, and cutting edge, that define the bifacial Keilmesser (Jöris 2006). Their only formal distinction from the latter is missing (simple edge retouched scraper) or only one-sided shaping (unifacially shaped scraper). The unifacially shaped scraper were shaped and thinned on their dorsal surface. As flaking platform served the back (Supplementary Information Fig. 35) or a striking platform was created at the distal posterior part (Fig. 1(2), Supplementary Information Fig. 36). One scraper has an additional striking platform at the base (Supplementary Information Fig. 35). Additionally, all unifacially shaped scrapers (see also Fig. 5(3)) were further thinned by invasive flaking from the cutting edge. Similar shaping patterns can be observed—although in a bifacial way—on the Keilmesser in our dataset (e.g., Figs. 1(3), 4(1), 5(2), 6(2)).

The term *Micoquian handaxes* is used here as a general expression for bifacial handaxe types (in contrast to "Halbkeile" with only one-sided shaping) which are found within the late Middle Paleolithic of central and eastern Europe (Bordes 1961; Bosinski 1967; Debénath and Dibble 1994). The artifacts analyzed in the present study (Fig. 5(1), Fig. 6(1), Supplementary Information Figs. 26–29) have a rather symmetric outline shape. Three are leaf-shaped (Fig. 5(1), Supplementary Information Figs. 26 and 27), and one has an ovate shape (Fig. 6(1)). The same components or prehensile and active zones as defined for the Keilmesser by Jöris (2006) are visible on the Micoquian handaxes (Fig. 5(1), Fig. 6(1)), although the distal posterior part or the second cutting edge is longer and the back subsequently shorter. They have a thick base and a rather short back, or its remnants connected to the back in the proximal part (see Fig. 8b). They possess a pronounced (Fig. 5(1)) or rounded tip (Fig. 6(1)) with the sharp cutting edge extending over the tip to the distal posterior part, potentially serving as second cutting edge (Veil 1995; Veil et al. 1994). Their cross-section is plano-convex (Fig. 6(1)) or irregular (Fig. 5(1)). In having a longer, preferred cutting edge opposite a shorter ("distal posterior part") sharp edge which is connected to a short back, the Micoquian handaxes in our dataset possess one of the typological criteria defined for the Micoquian handaxes or "Micoquekeile" (Bordes 1961; Bosinski 1967; Debénath and Dibble 1994).

Artifact Types Analyzed with Attribute Analysis

As stated above, we took additional tools from the three assemblages to make a dataset of 163 tools to help interpret the variability of the tools in question in the larger context of late Middle Paleolithic tools. We did not include questionable tools, like preforms, indeterminate bifaces, or truncated faceted pieces, which might have been cores (Dibble and McPherron 2006). To make the analysis and the results clear and understandable,

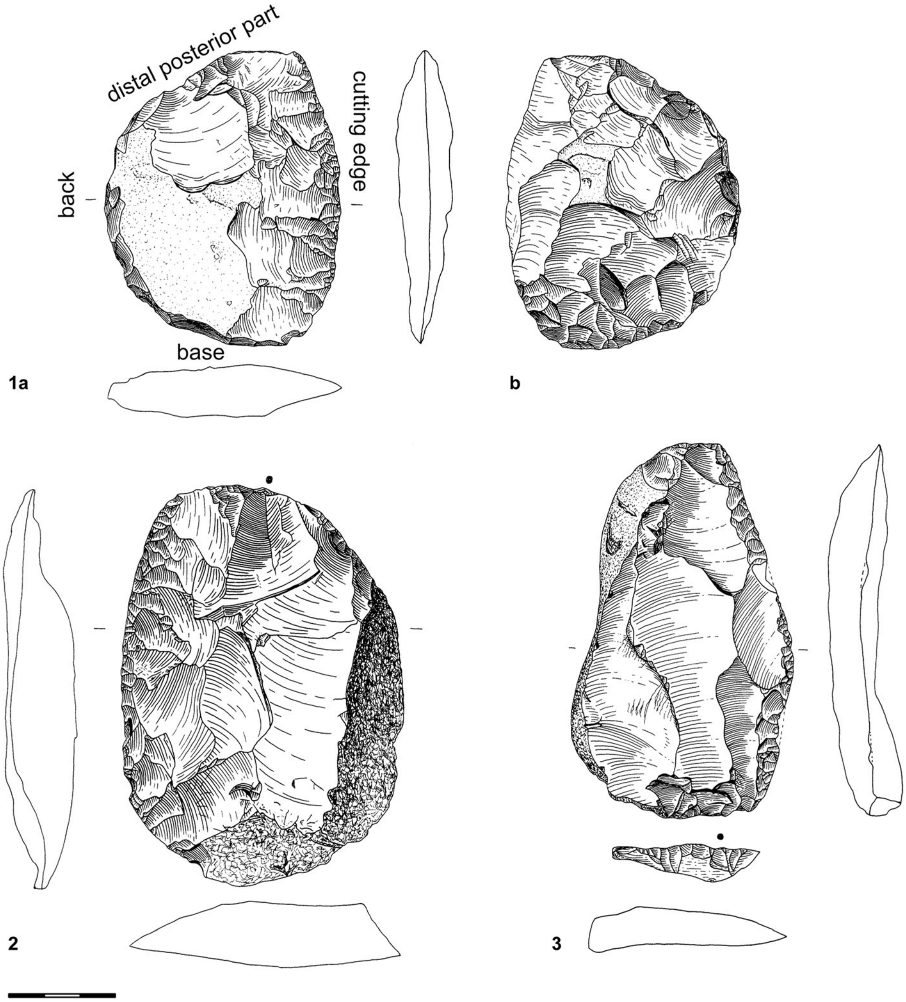

Fig. 4 Examples of stone tools from the excavated site Pouch-Terrassenpfeiler used in this study. (1a, b) Keilmesser, 2004:8679,55; (2) unifacially shaped scraper with Keilmesser-like morphology, 2004:8679,52; (3) simple scraper with Keilmesser-like morphology, 2004:8679,9. On the Keilmesser (1), the morphological components defined by Jöris (2006) are highlighted. Drawings: M. Weiss

we rather focused here on established and well-known late Middle Paleolithic tool types (e.g., Bosinski 1967; Debénath and Dibble 1994; Veil et al. 1994). Only the groups of simple scrapers and unifacially shaped scrapers with a Keilmesser-like morphology were separated by us in the framework of the present study.

Some typical Micoquian tool types in the dataset are *Faustkeilblätter* (Fig. 7(1)), bifacial points (Fig. 7(2)), bifacial scrapers (Fig. 7(3)), and leaf-shaped scrapers (Fig. 7(4)). The *Faustkeilblatt* is a handaxe-like, flat, bifacially shaped tool, defined by a proximal, natural or retouched base, a pronounced tip, and a cutting edge opposite blunted edge without a back (Bosinski 1967; Veil et al. 1994). Leaf-shaped scrapers are mostly ovate with a transverse axis of symmetry perpendicular to the cutting edge (Veil et al. 1994) and a blunt zigzag-shaped edge opposite the cutting edge (Bosinski 1967).

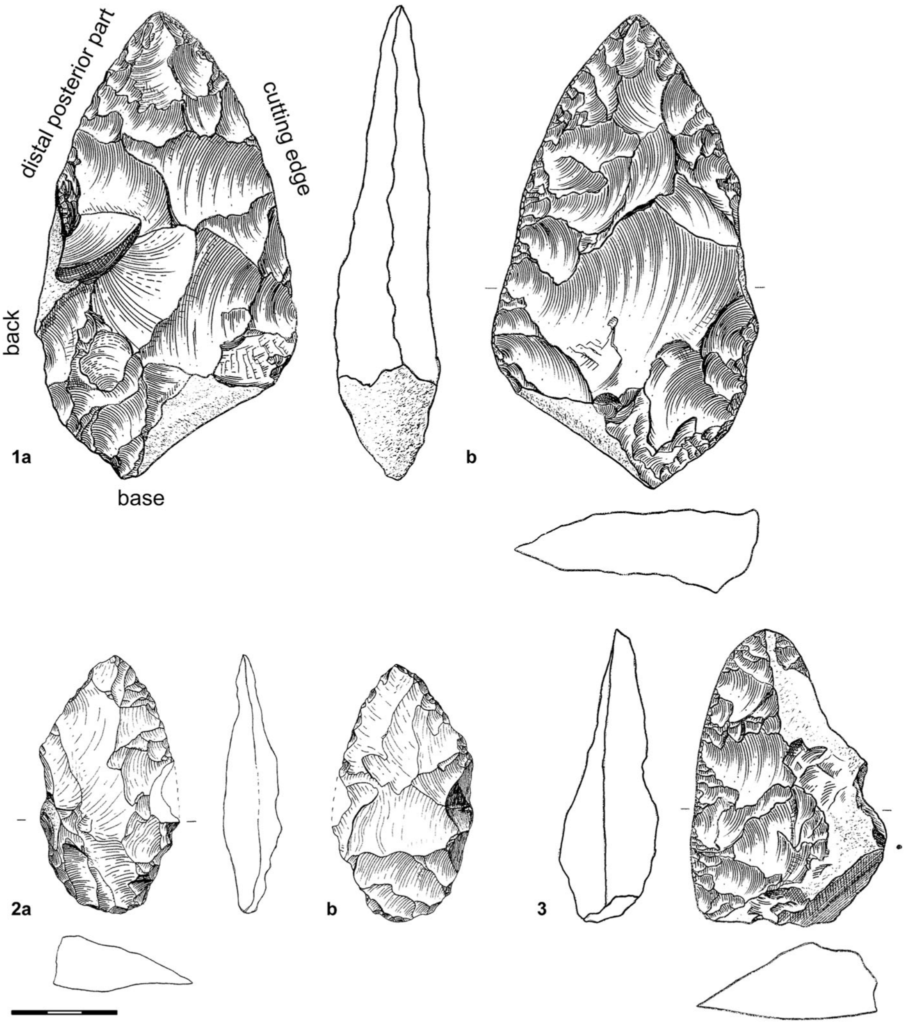

Fig. 5 Examples of stone tools from the Goitzsche collection used in this study. (1a, b) Handaxe, SSZ-16/1/306; (2a, b) Keilmesser, SSZ-7/1/98; (3) unifacially shaped scraper with Keilmesser-like morphology, SSZ-16/1/324. On the Micoquian handaxe (1), the morphological components defined by Jöris (2006) for Keilmesser and applied to Micoquian handaxes are highlighted. Drawings: (1, 3) W. Bernhardt, (2) M. Weiss

Bifacial scrapers are characterized by one or more cutting edges and an irregular overall shape (Debénath and Dibble 1994).

Methods

OSL Dating

To further constrain the available chronostratigraphy for the sediments connected to artifact find locations, luminescence dating was applied to three samples collected from

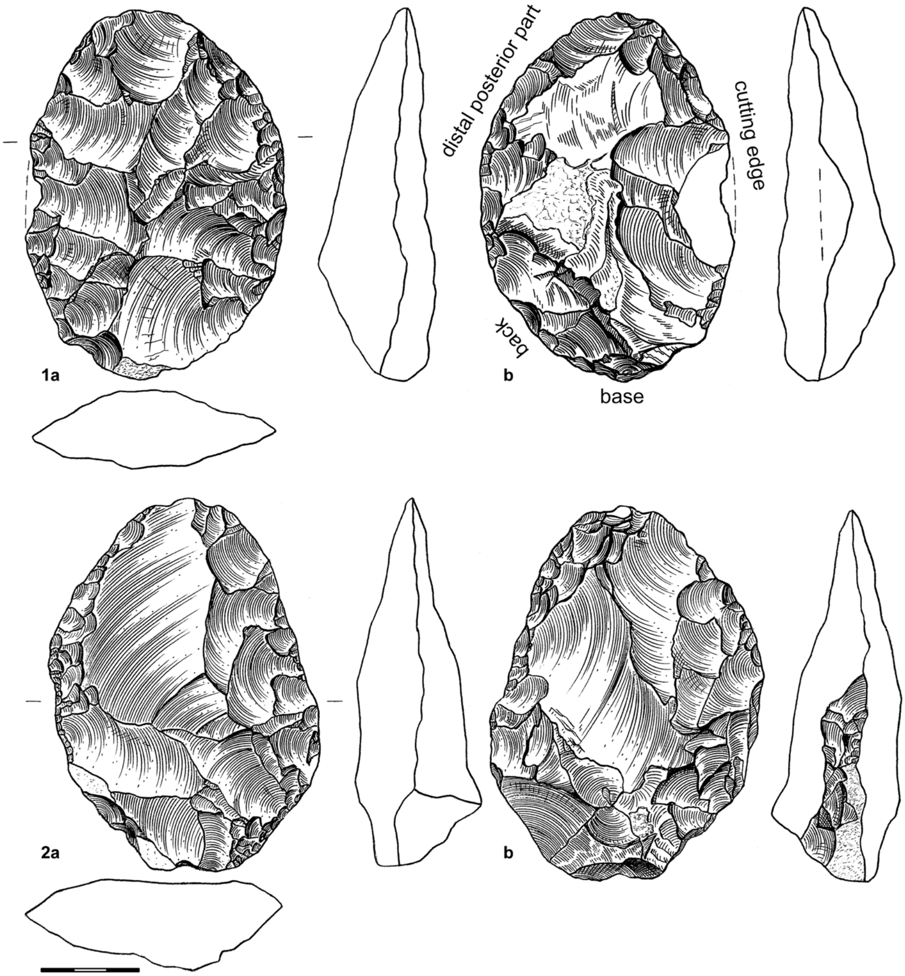

Fig. 6 Examples of stone tools from the Löbnitz collection used in this study. (1a, b) Handaxe, Lö/904-271340, despite a thick part at the proximal left edge close to the base (1b), there is no back on this artifact; (2a, b) Keilmesser type "Lichtenberg", Lö/212-271343. On the Micoquian handaxe (1), the morphological components defined by Jöris (2006) for Keilmesser and applied to Micoquian handaxes are highlighted. Drawings: W. Bernhardt

the Lower Terrace sediments exposed at the northern rim of the quarry field Rösa-Sausedlitz within the Goitzsche mine (see "Materials" section).

Equivalent dose (D_e) measurements on coarse-grained quartz were undertaken using an automated Risø TL/OSL reader equipped with blue light-emitting diodes (Botter-Jensen et al. 2000). The OSL signal was detected through an ultraviolet transmitting Hoya U-340 filter. To check for feldspar contamination within the quartz crystal lattice, IR LEDs (870 nm) were used and the IR-signal was detected through a filter combination of BG-3 and BG-39. Irradiation was provided by calibrated $^{90}Sr/^{90}Y$ beta sources (Botter-Jensen et al. 2000).

For OSL dating, the single-aliquot regenerative dose (SAR) protocol of Murray and Wintle (2003) was used and the parameters (pre- and cut-heat temperatures) for the

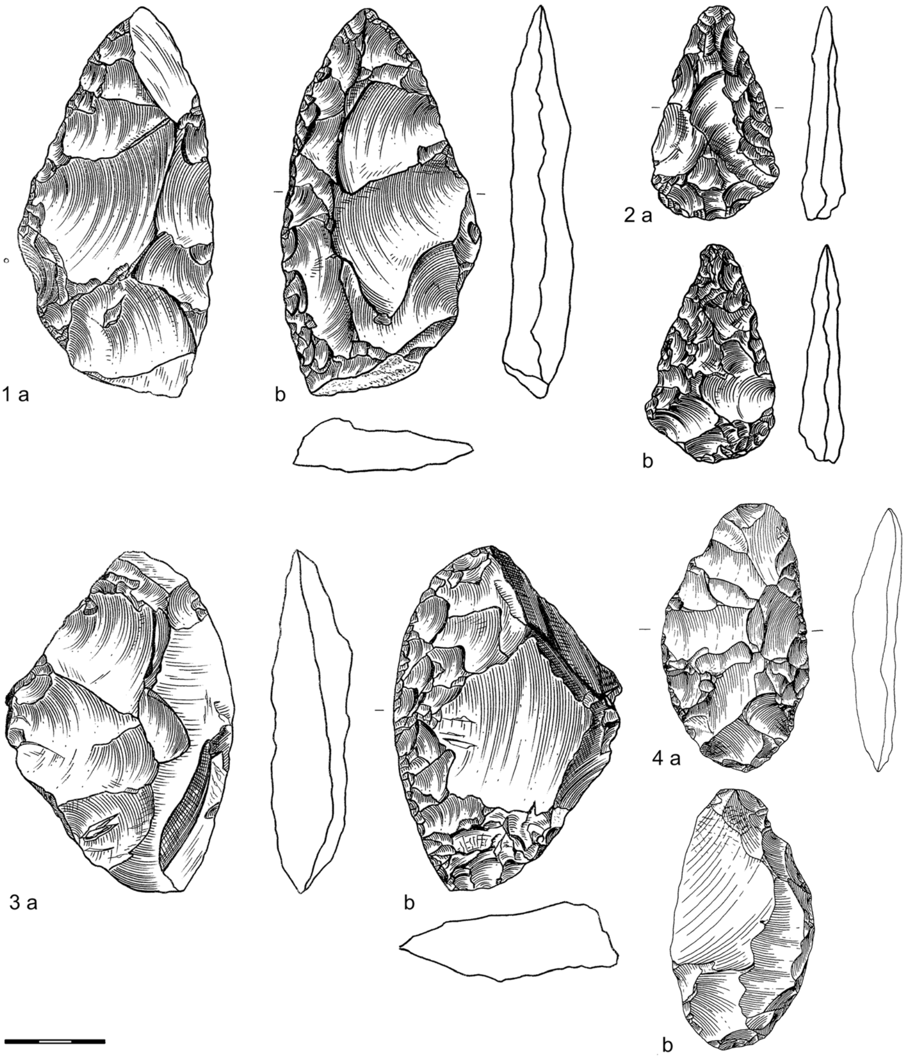

Fig. 7 Micoquian tool types incorporated in the attribute analysis. (1a, b) Faustkeilblatt, 9852:1:1; (2a, b) bifacial point, 2004:25473; (3a, b) bifacial scraper, SSZ-16/1/270; (4a, b) leaf-shaped scraper, 2004:8679,4. Drawings: (1–3) W. Bernhardt, (4) M. Weiss

SAR-procedure were defined by applying dose-recovery tests on samples Ros-1 and Ros-2. Finally, pre- and cut-heat temperatures were set to 200 °C.

For equivalent dose measurements, the SAR protocol was applied to 2 mm sized aliquots. Dose response curves for quartz were created by inserting four to five dose points. During analysis, all aliquots showing recycling or IR-depletion ratios deviating > 15% from unity were rejected. The dose rate was obtained by gamma-ray spectrometry at the TU Bergakademie in Freiberg. The activity of ^{238}U, ^{232}Th, and ^{40}K was measured on a p-type detector using about 1000 g of the dried sample material. The cosmic dose rate was assumed based on Prescott and Hutton (1994). The water content was assumed to be 15 ± 5%. Dose rate conversion factors were taken from Guerin et al. (2011).

Lithic Analysis

3D analyses were conducted on surface models generated using a BIR Actis 225/300 CT-scanner with resolutions of 36 to 69 μm. Unless stated otherwise, data preparation and management, as well as statistical analyses were done in R (R Core Team 2016).

3DGM

We used 3DGM shape analysis to analyze the relationship of Keilmesser, handaxes, simple scrapers, and unifacially shaped scrapers with a Keilmesser-like morphology with regard to the 3D outline shape of the artifacts. In contrast to Elliptical Fourier Analysis of 2D outlines, which has already been applied to late Middle Paleolithic stone tools (Iovita 2009; Serwatka 2015), 3DGM is more suitable for the backed asymmetric tools in question, as the 3D curves cover additionally the thickness and extension of the base and back (for the application of related 3D EFA, see e.g., Chacón et al. 2016). Moreover, among other studies based on processing 3D scans (e.g., Archer et al. 2017; Grosman et al. 2008; Lin et al. 2010; Morales et al. 2015a; Morales et al. 2015b), 3DGM has been successfully applied to bifacial stone artifacts, namely Stillbay points of the southern African MSA (Archer 2016; Archer et al. 2015, 2016).

Given our research goals, we used the following protocol to landmark the tools. The landmarks were placed using "Landmark Editor" (IDAV, UC Davis) and processed in R using the package "geomorph" (Adams and Otarola-Castillo 2013). On each artifact, we recorded 82 landmarks spread over six curves. Five landmarks were fixed landmarks (Fig. 8): the point of the tip or the distal end of the cutting edge, the proximal end of the cutting edge, the ventral and dorsal inflection point between the base and the back, and the point at the border between the back and the distal posterior part. Between these points slide the equidistant semi-landmarks of the six curves: the cutting edge, the ventral and dorsal curve of the base, the border line between the base and the back, the dorsal and ventral curve of the back and the distal posterior part (Fig. 8). We placed our landmarks only at the edges and not on the surface of the artifacts, as the curves of the cutting edge, the distal posterior part, the base, and the back capture already the most important aspects of the Keilmesser morphology in three dimensions. For the analysis of the surface, we used Thickness Mapping (see below) computed from the 3D scans rather than a surface landmark approach. As we stated above (see "Lithic Analysis" section), damaged pieces (e.g., broken tip) were excluded from our analysis. However, we included one piece from Pouch (Fig. 4(3)) and a few pieces from the collected assemblages (Löbnitz: 4, Goitzsche: 1, e.g., Fig. 5(2), Fig. 6(1)) that had small-scale recent edge damage, either due to accidents during recovery (Pouch) or due to mining (Goitzsche, Löbnitz). On the damaged parts, semi-landmarks were not placed within the concavity of the damage but instead on either end of the preserved original edge. Sliding and the equalized dispersion of the semi-landmarks (see below) then remodeled the original curve of the damaged part of the edge.

3DGM analysis, including Procrustes superimposition, was performed using functions from the R package "Morpho" (Schlager 2016). To standardize orientation, scale,

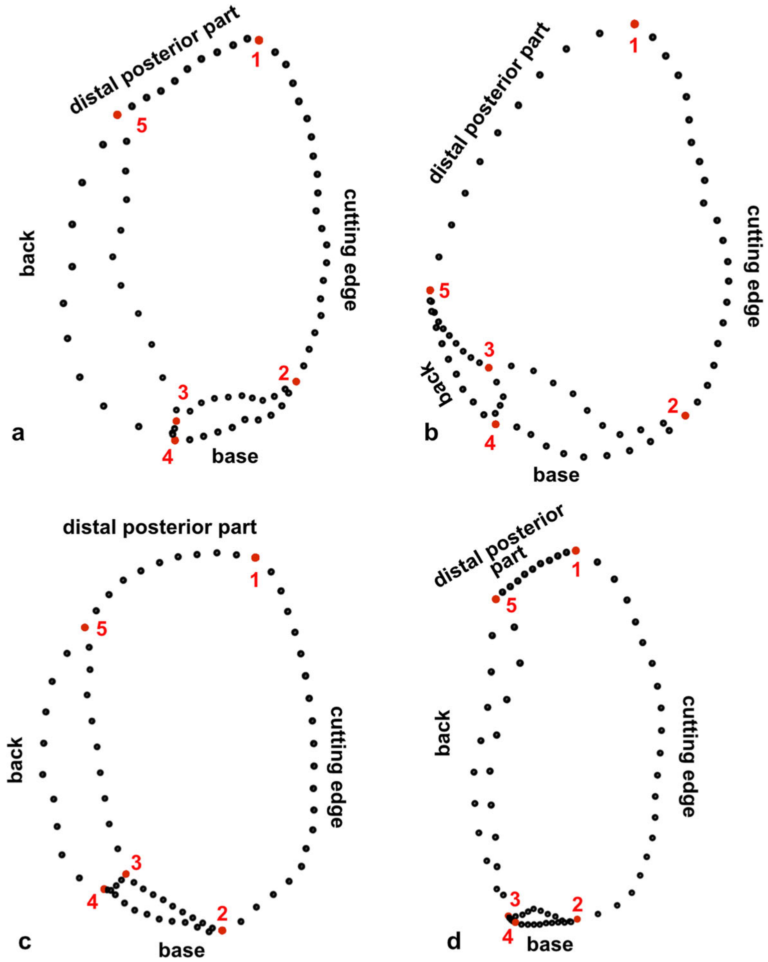

Fig. 8 Position of the 82 landmarks along the curves of every typological tool class. The red dots mark the fixed landmarks (1 to 5): on the tip, the proximal end of the cutting edge, the dorsal and ventral inflection point between the base and the back, and the distal end of the back. Black dots mark the equally spaced semi-landmarks sliding along each curve: 19 on the cutting edge, 9 each on the ventral and dorsal outline of the base, 4 on the border curve between the base and the back, and 9 each along the dorsal and ventral outline of the back and the distal posterior part. **a** Keilmesser; **b** handaxe; **c** unifacially shaped scraper with Keilmesser-like morphology; and **d** simple scraper with Keilmesser-like morphology

and location, the three-dimensional coordinates were translated using Procrustes superimposition (Rohlf and Slice 1990). A principal component analysis was then performed on the translated set of individual landmark configurations to analyze similarities and dissimilarities between artifact shapes. The first two principal components, accounting for ~61% of the variation (see Fig. 10), were then plotted. The spatial median or mediancenter (Bedall and Zimmermann 1979; Gower 1974) was calculated for each group to illustrate the respective center of variability. To analyze further which parts of the tool (e.g., cutting edge or back) are most sensitive to shape variation between the different tool types, we plotted the major axis of variation based on the PCA. The plot (see Fig. 11**)** illustrates the main variation, as it plots the positive shape on PC1 and PC2 onto the mean shape for (a) each tool type and (b) for all tool types together.

Thickness Mapping

To find out how thickness is distributed in relation to the different morphological parts of each artifact and group (e.g., back or cutting edge), we mapped the thickness based on the 3D models. The assumption here is that if tools were handled in a similar way in the past, if they had comparable functions, or if they were shaped and retouched using the same strategies, their thickest and thinnest areas should be distributed in a comparable way (e.g., thicker towards the prehensile parts, thinner along the active or cutting edges). In other words, if two tool types are related, their volume should have been managed in a similar way by the knapper and they should show comparable thickness distribution patterns.

We used the high-resolution 3D artifact scans to examine thickness distributions relative to the overall morphologies of the artifacts across the collection. To this end, we first standardized orientations and scales. To accomplish the former, we used manually placed fixed landmarks (Fig. 8) to define two vectors: (a) tip to the inflection point of the base and back and (b) from the point between the back and the distal posterior part to the proximal end of the cutting edge. Since the inflection point between the base and back is defined by two landmarks (Fig. 8), the mean coordinates of the latter were used to define vector (a). The artifact meshes were then re-oriented so that both vectors were parallel to the xy plane with the first one at $z = 0$ and with the tip pointing left and the main cutting edge pointing down (Fig. 9). Surface coordinates and landmarks were then translated to a common center, defined as the mean coordinate at the origin ($x = 0$, $y = 0$, $z = 0$), and re-scaled to a common maximum surface-to-center distance of one.

Following this 3D orientation, translation, and scaling procedure, a grid was overlaid on the plan-view representation of the artifacts, and the maximum observed distance between surface coordinates ($n > 10$) per grid cell, corresponding to the maximum thickness at that spot, was recorded. We used a baseline grid resolution of 0.01 or 1% of the maximum distance from the center of an artifact to its surface. The plan-view coordinates of the grid were then translated to a common center defined by the median, to ensure an even distribution of areas around the two main axes. We identified the grid cells with the highest 10% thickness values and computed their average coordinates (*tp*—2 in Fig. 9). This represents an arbitrary cutoff to capture the thickest area of the piece.

We evaluated similarities and differences in the relative location of these thickest parts across identically oriented artifacts of different artifact classes through a 2D scatterplot showing the magnitude and angle of the vectors defined by the center and thickest part (*tp*) coordinates (1 and 2 in Fig. 9). All analyses were done in R v3.4.2 using the following packages: "geomorph" v3.0.5 (Adams and Otarola-Castillo 2013), "Rvcg" v0.17 (Schlager 2017), Morpho v2.5.1 (Schlager 2016), "data.table" v1.10.4-2 (Dowle and Srinivasan 2017), "pracma" 2.0.7 (Borchers 2017), and "ggplot2" v2.2.1 (Wickham 2009).

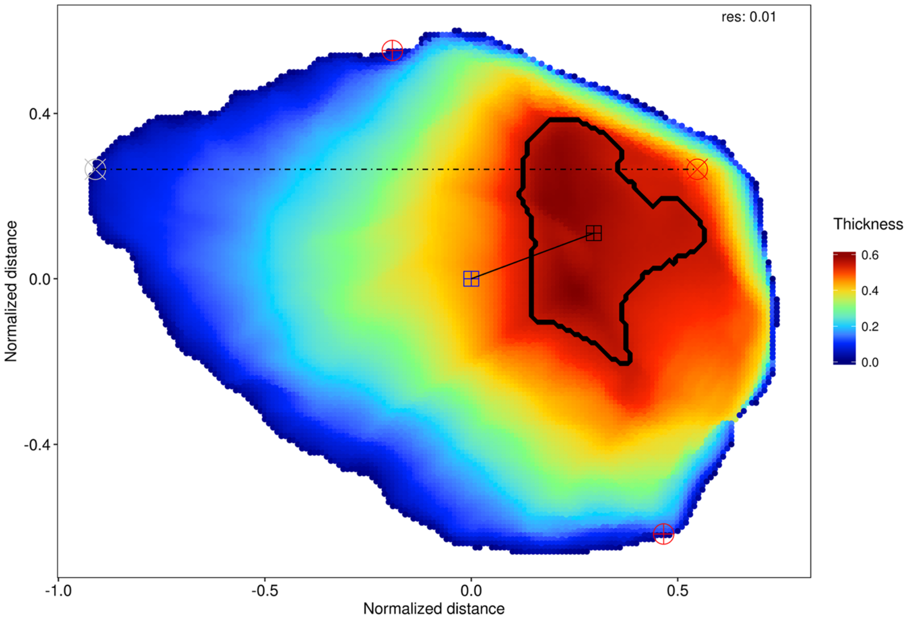

Fig. 9 Translated, scaled, and oriented thickness map of artifact LBZ-50/1/146 annotated with points of interest: (1) center (median) of the artifact cross-section along the plane defined by the tip (5), base/back inflection midpoint (4), adjusted base and back end-point coordinates (6 and 7), and center (2) of the area (3) with the top 10% thickness. The magnitude and direction of the vector defined by 1 and 2 are used to compare thickness distributions across the entire collection. The tip of the artifact is oriented towards the left, base to the right, distal posterior part upwards and cutting edge downwards

Edge Angles Computed from the Thickness Maps

Edge angles were computed from the thickness maps along curves defined by the edge landmarks. Here we focus on the curves of the active zones cutting edge and distal posterior part, as the prehensile back and the base have the largest edge angles by definition. These curves were re-sampled to either a specific number of equidistant semi-landmarks ($n = 30$), or to semi-landmarks located at specific distances (0.5 mm) from each other, using the “digit.curves” function of the “geomorph” R package (Adams and Otarola-Castillo 2013). The former allowed specific edge sections to be compared across artifacts and tool classes, while the latter allowed comparisons between all edges. The angles were measured by sampling the thickness maps at a distance of 5 mm from each semi-landmark along a line defined by the normal of the arc formed by the semi-landmark and its immediate neighbors. In case of perfectly linear edge sections, the normal of the line connecting two adjacent semi-landmarks was used instead.

For measuring the edge angles, it is important that the edges are preserved in a good condition, especially for the artifacts from the collected assemblages. All of the pieces from the excavated assemblage of Pouch show a fresh edge preservation. The artifacts from the two collected assemblages have fresh edges (8) or show light edge damage (8), except two pieces that are slightly rolled. For the latter two as well as the other lightly damaged tools, the not intrusive damage had only very limited influence on the result as the angles where measured at a distance of 5 mm from the edge. At this distance, the original angles where preserved.

Attribute Analysis

All the 29 artifacts in this study were separately measured using a conventional attribute analysis (Ertmer 2012; Schäfer 1993; Weber 1986; Weiss 2015; Weiss et al. 2017). We used this method as independent approaches to analyze the same tools (Table 1) with regard to different variables like conventionally measured minimum and maximum edge angles and intensity of retouch. With the help of a previously built dataset (Weiss 2015) and attribute data from the recently finished analysis of Löbnitz, we were, as a second step, able to incorporate attribute data of a larger sample of 163 tools in our study and to interpret the variability of Keilmesser, handaxes as well as unifacially shaped and simple scrapers with Keilmesser morphology in the context of other late Middle Paleolithic tools from the same assemblages (Table 2).

To make the flake tools comparable to bifacial tools, the length of the former was not measured along the flaking axis of the blank. Instead, and this is mainly important for transversal scrapers, where the distal edge forms the working edge, the length of the former was also measured along the axis of the piece, i.e., following the direction of the cutting edge.

A principal component analysis was performed on five attributes of each artifact, using the R package "vegan" (Oksanen et al. 2016): (1) the length-width-index (LWI) or elongation, calculated from the maximum length divided by the maximum width, (2) the width of each tool relative to its thickness, expressing the flatness of the artifact (Bordes 1961; Debénath and Dibble 1994), (3 and 4) the minimum and maximum edge angle of the cutting edge measured with a goniometer up to a distance of 5 mm from

Table 2 Late Middle Paleolithic tools incorporated in the attribute analysis

Tool type	Goitzsche	Löbnitz	Pouch	Total
Backed knife	1	0	6	7
Bifacial point	2	1	0	3
Bifacial scraper	3	5	0	8
Edge retouch	4	1	4	9
Faustkeilblatt	3	1	0	4
Handaxe	3	9	0	12
Keilmesser	4	25	3	32
Leaf-shaped scraper	6	6	2	14
Simple scraper	12	12	16	40
Simple scraper K.-M.	0	0	5	5
Unif. shaped scraper	4	5	6	15
Unif. shaped scraper K.-M.	1	0	3	4
Macroscopic use-wear	0	0	10	10
Total	43	65	55	163

the edge, and (5) the ratio of the retouched to non-retouched edge length to get a measure for the intensity and quantity of edge modifications for each piece. For the application of PCA on stone artifacts, see e.g., Weiss et al. (2017), among others (e.g., Golovanova et al. 2016; Scerri et al. 2016).

Results and Preliminary Discussion

New Luminescence Ages and Age of the Artifacts

Table 3 shows a summary of the OSL dating results obtained from the sediments exposed at the Goitzsche pit.

The new luminescence ages support the previous chronological framework and indicate various fluvial aggradation periods during the last glacial cycle. The bottom unit of the Lower Terrace sequence in the Goitzsche quarry yielded an OSL age of 55 ± 5 ka (Fig. 3), the middle part of the sequence was deposited at around 30 ka, and the upper part of the fluvial sand and gravel gives an OSL age of 17 ± 2 ka. The new OSL ages confirm an onset for the accumulation of the Lower Terrace during the beginning of MIS 3 after major erosion in MIS 4. This was already suggested in several studies of last glacial river systems of the northwestern European plain (Mol 1995, 1997; Mol et al. 2000; Van Huissteden et al. 2001).

The new OSL ages, together with the previous radiocarbon and luminescence dates for the Lower Terrace sequence (Fig. 3), indicate an early MIS 3 age for the excavated artifacts of Pouch as well as for the collected artifacts from the Goitzsche mine and the Löbnitz quarry. The majority of the finds from Goitzsche were directly collected from the base of the fluvial sequence and its lower 4 m (Weiss 2015), or below the Lower Löbnitz Horizon respectively. This horizon caps the Lower Coarse Unit which contains the artifacts (Fig. 3). The 1σ range of the radiocarbon ages, ~40,000 and ~31,000 calBP, for the Lower Löbnitz Horizon as well as the late Middle Paleolithic character of the finds suggests that they have an age of between 55 and 40 ka. For Löbnitz, the chronological attribution is more difficult as the finds were not collected from their primary position but instead from the coarse gravel dump as a result of mining activities. But the fact that Löbnitz is part of the same fluvial terrace as the close by sites Pouch and Goitzsche, as well as the general Middle Paleolithic character of the assemblage, let us infer a comparable age for the artifacts. Still, it might be possible that parts of the assemblage, especially undiagnostic flakes, might be of a younger age.

Table 3 Nuclide concentrations, dose rates and OSL age estimates. Abbreviations: U, uranium; Th, thorium; K, potassium; CAM, Central age model; DR, dose rate; De, equivalent dose

Sample ID	U (ppm)	Th (ppm)	K (%)	Cosmic dose (mGy/a)	H_2O (%)	Total DR (mGy/a)	De (CAM)	Age (ka)
Ros 1	1.1 ± 0.3	3.2 ± 0.1	1.4 ± 0.01	0.15 ± 0.01	15 ± 5	1.7 ± 0.1	91.6 ± 4.7	55.1 ± 5.1
Ros 2	1.6 ± 0.3	4.1 ± 0.2	1.5 ± 0.01	0.19 ± 0.02	15 ± 5	2.0 ± 0.1	61.3 ± 3.7	30.8 ± 2.8
Ros 3	0.7 ± 0.2	2.5 ± 0.1	1.2 ± 0.01	0.20 ± 0.02	10 ± 5	1.6 ± 0.1	27.0 ± 2.1	17.0 ± 2.0

However, this issue can be neglected for our present study as we included only diagnostic Middle Paleolithic tool types from Löbnitz. In general, the stone tools compared in the present analysis are roughly contemporaneous and belong to the end of the late Middle Paleolithic.

Lithic Analysis

3DGM

Figure 10 displays the first two principal components (~61% of the variability) in shape space and the position of each artifact included in this study. The spatial median or mediancenter (Bedall and Zimmermann 1979; Gower 1974) was calculated for each group to illustrate the respective centers of variability. In general, three trends in the different tool types are visible: (1) Keilmesser show a large range of variability compared to the other tools within the dataset, (2) simple scrapers and unifacially shaped tools with a Keilmesser-like morphology overlap with the variation of Keilmesser in the center of the plot, and (3) three of the four handaxes form a separate group at the right margin, fully beyond the range of the Keilmesser.

PC1 accounts for 43.4% and PC2 for 17.3% of the variability. To find out which 3D outline shape differences are caused by these components, the shape variation according to the landmark positions of the first two principal components is displayed in Fig. 11. This is illustrated by a vector showing a magnitude of three standard deviations of each landmark. PC1 is mainly related to the broadness of the tool (or more elongated tools for low values of PC1), the reduction of the cutting edge, reduction and shift of

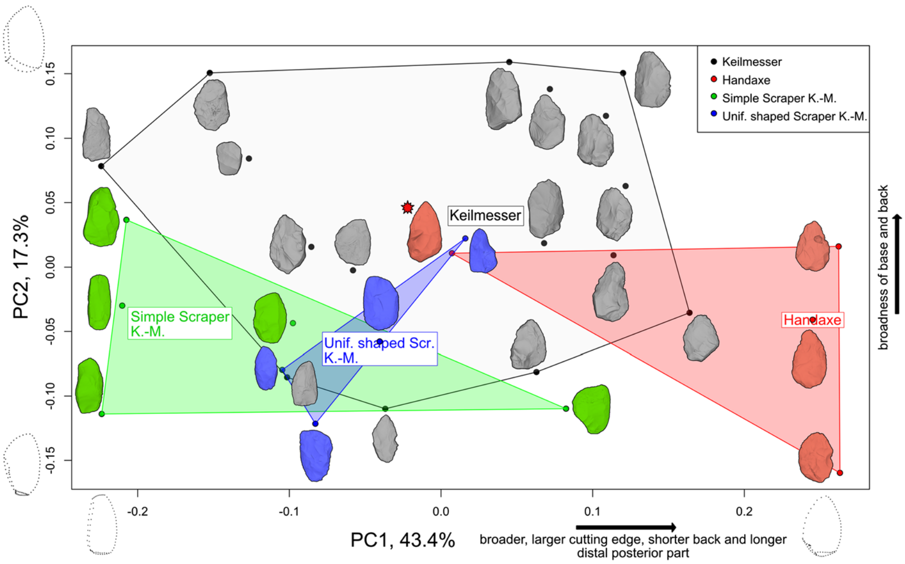

Fig. 10 The first two principal components of the three-dimensional shape space. The group labels mark the spatial median of each group. In dotted lines, next to the axis, are the mean shapes for the extremes of PC1 and PC2. PC1 seems to be related to the broadness of the tool as well as the extension of the back. Shape change related to PC2 is connected to the broadness of the base and the back. The star marks the outlier from the cluster of three handaxes

the distal posterior part and the back, and the shift of the base. Shape difference influenced by PC2 might mainly be related to the broadness or "massiveness" of the base and the back (Fig. 10; Fig. 11).

That Keilmesser show the largest variability within our dataset confirms the Keilmesser 2D outline shape analysis by Serwatka (2015) and the notion that Keilmesser were defined with highly variable shape (Jöris 2006, 2012). As suggested before (e.g., Iovita 2010, 2014, Jöris 2001, 2006; Urbanowski 2003), the variability in morphology might be due to having Keilmesser in our dataset that represent different stages of reduction and resharpening.

Within variation in broadness along PC1, the more elongated simple scrapers with their extended back form a group at one extreme (Fig. 10), whereas the broader handaxes with their short back and their extended distal posterior part lie at the other extreme. Especially the extension of the back and the distal posterior part separates three of the five simple scrapers and three of the four handaxes as more separate morphological groups. The latter fall completely outside the range of variation explained by PC1 compared to the other tools in our dataset. In contrast, the unifacially shaped scrapers largely overlap variability in Keilmesser in the center of the plot.

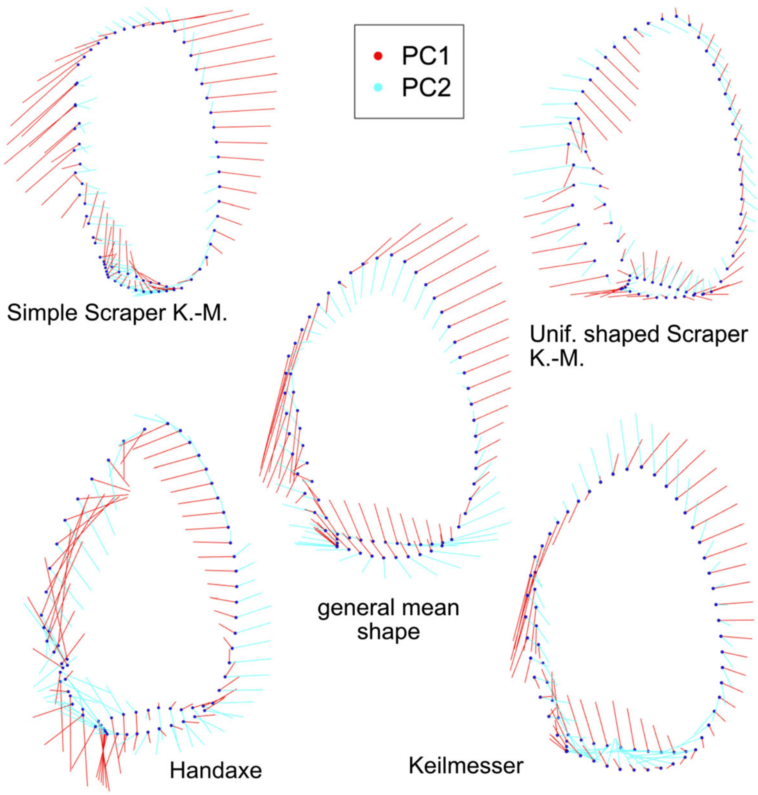

Fig. 11 Vectors showing shape variation according to the first two principal components in tangent space on the general mean shape, the mean shapes of simple edge retouched and unifacially shaped scrapers with Keilmesser-like morphology, and the mean shapes of handaxes and Keilmesser. The vector distance equals three standard deviations of each landmark position to illustrate the intensity of shape change in certain areas

The 3D outline shape differences in simple scrapers might be because they are only slightly altered flake tools. In contrast, 80% of the Keilmesser and handaxes were produced on flint nodules or natural flint pieces. The edges of the simple scrapers with Keilmesser-like morphology were only slightly retouched so that the shape of the flake blank still has a major influence on the final tool morphology. It seems that special blanks, especially flakes with natural backs, were chosen to produce these tools. Given the low intensity and quantity of edge retouch, the variability in the 3DGM plot (Fig. 10) reflects the variability of the flakes that were chosen for the simple scrapers with Keilmesser-like morphology. Given the fact that the simple scraper variability overlaps with those of unifacially shaped scrapers and Keilmesser in the center of the plot and given that one Keilmesser plots close to the group of simple scrapers on PC1, simple scrapers are at least partly within the range of Keilmesser variability. Additionally, the positions of their spatial group medians are closer to each other in comparison to the mediancenter of handaxes. A larger dataset could potentially clarify whether simple scrapers with Keilmesser-like morphology form a separate group from Keilmesser.

In contrast to the other tools in our dataset, most of the Micoquian handaxes fall outside the range of Keilmesser variability along PC1. If we consider the limited area of overlap with Keilmesser as well as the one handaxe marked with a star in the plot (Fig. 10) as an outlier, handaxes form a distinct tool group within the present dataset. The shorter back and the prolonged distal posterior part results as well in a more symmetric 3D outline shape, illustrated in the mean 3D outline shape of the group of three handaxes on PC1 (Fig. 10). This is in accordance with the definition of Keilmessergruppen handaxes having a more symmetric distal part (e.g., Veil et al. 1994). In other words, as the quantitative method suggests a conclusion similar to the former techno-functional and typological analysis, it can be inferred that symmetry might in fact be an important part of the Micoquian handaxe tool concept (e.g., Veil et al. 1994). It may be that the one handaxe marked with a star in the plot (Fig. 10; Fig. 5(1)) should be classified as Keilmesser instead, despite having a more symmetric distal part. Although the distal posterior part of this artifact is extended and sharp, the back is longer than for the other three Micoquian handaxes. If so, handaxes would be the tool type showing the lowest 3D outline shape variability. This would make Micoquian handaxes in our dataset a very standardized tool type in comparison to the others, keeping in mind that this is a very preliminary interpretation because the low shape variability might be related to the low sample size.

One of the major shifts in landmarks is related to the longest cutting edge (Fig. 11) and can be interpreted in relation to general tool reduction patterns in the Micoquian which focus on edge angle maintenance and the resharpening of primarily one cutting edge (Iovita 2014; Serwatka 2015). Although the sample sizes for most of the types except Keilmesser are low, this main landmark shift, related to primarily one cutting edge together with reduction of the distal posterior part and the back, could be observed on all of the types included in this study. Following Iovita's hypothesis (Iovita 2009, 2010, 2014) outlined earlier, similar reduction patterns can be observed on the typologically distinct tool classes. This may point to a comparable functionality of the tools analyzed here and their morpho-functional components. Furthermore, this reduction pattern stands in contrast to the reduction trajectories visible in Acheulean handaxes (Serwatka 2015), which have been shown to result primarily in the rejuvenation of the tip area (Iovita and McPherron 2011; McPherron 1995, 1999, 2000). This points to a different tool concept for Micoquian handaxes which seems to be more related to the other Micoquian tool forms than to classical Acheulean handaxes. It should be the subject of future research on a larger sample of Micoquian handaxes whether the reduction was focused only on the maintenance of the cutting edge solely or also on the maintenance of shape as has been shown for the MTA (Iovita and McPherron 2011).

Thickness Mapping

Figure 12 shows examples of thickness maps from Keilmesser, handaxes, and simple edge retouched and unifacially shaped scrapers with Keilmesser-like morphology. Figure 13 shows the standardized location (distance and direction) of the average thickest 10% part of each artifact relative to its center.

Consistent with the results of the 3DGM analysis, Keilmesser are the most variable tool class considered here in terms of the location of their thickest part, encompassing virtually the entire range of variation of the other classes. Despite their high variability, a clear tendency for their thickest area to be located towards the back (opposite the cutting edge) and the base can be observed (Fig. 13). This is expected as Keilmesser are defined as having an asymmetric cross-section with the back as the thickest part of the

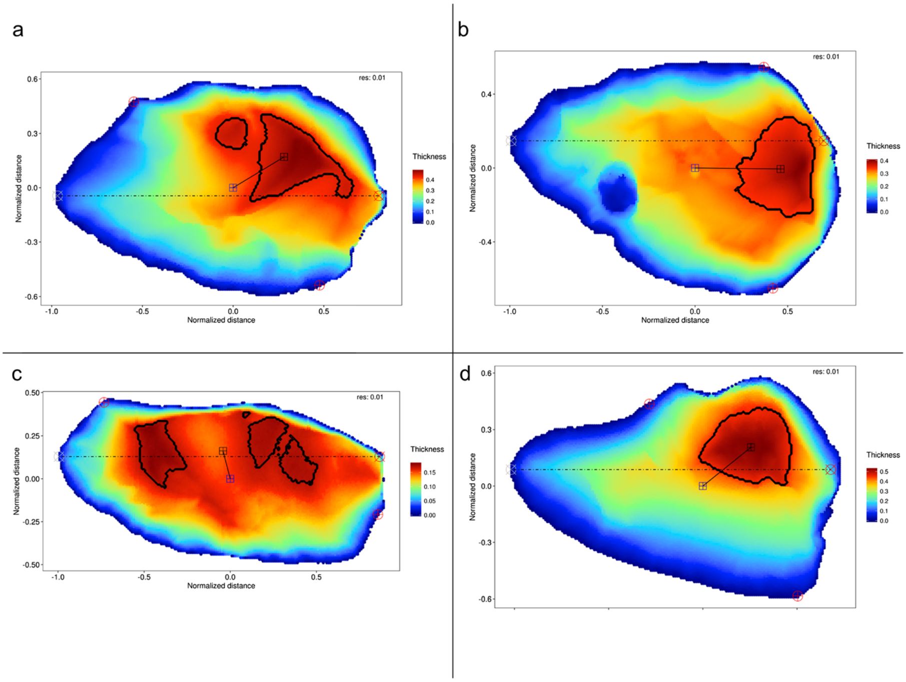

Fig. 12 Thickness distribution maps. **a** Keilmesser from Löbnitz, LBZ-08/1/4; **b** handaxe from Löbnitz, LBZ-08/1/27; **c** simple scraper with Keilmesser-like morphology from Pouch, 2004:8679,19; **d** unifacially shaped scraper with Keilmesser-like morphology from Goitzsche, SSZ-16/1/324. The tip of each artifact is oriented towards the left, base to the right, distal posterior part upwards and cutting edge downwards. For symbols, see Fig. 9

piece (Jöris 2001, 2006, 2012). Four Keilmesser match with the handaxe cluster showing similar degrees of symmetry in having a thickness distribution aligned with their center and oriented towards the base. But, in contrast to the morphology of handaxes, they possess a prolonged back and consequently a shorter distal posterior part (SI Lö/1020-271347 (SI Fig. 9), Lö/212-271343 (Fig. 6(2); SI Fig. 8), LBZ-06/1/117 (SI Fig. 4), LBZ-49/1/96 (SI Fig. 3)), resulting in a rather asymmetric overall morphology. Another feature of the Keilmesser morphology is that the thinnest areas are connected to the cutting edge and the tip surface area (Fig. 12a), but also including the distal posterior part. In other words, the thickness distribution shows that the thinning of the tip surface area was important for the tool concept and/or resharpening strategies (e.g., Jöris 2001). Generally, we can infer that Thickness Mapping confirms the typological and techno-functional definitions (e.g., Bosinski 1967; Jöris 2006, 2012; Veil et al. 1994) established for this tool type, resulting in a suitable quantitative method for detecting the specific components of a Keilmesser-like tool. Therefore, this method will now be applied to the other tool types selected for this study to detect the morpho-functional Keilmesser components and reveal similarities and differences.

The thickness distribution of simple scrapers with Keilmesser-like morphology reveals important similarities with Keilmesser tools: the distribution is highly variable and is largely encompassed by the Keilmesser range, and like Keilmesser, they show a tendency for the thickest area to be located close to the back (Fig. 13). They further share a similar distribution of the thinnest parts: the cutting edge and the tip region (Fig. 12c), including the distal posterior part. As these tools are only retouched at the tip and along one cutting edge, a thickness distribution matching those of Keilmesser

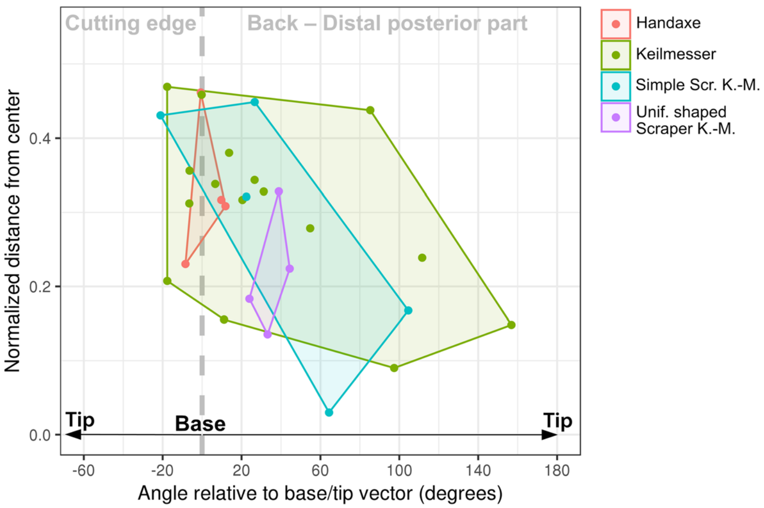

Fig. 13 The normalized distance of the top 10% thickness in relation to the angle relative to the base/tip vector. If the angle = 0 (dotted line), the thickness is aligned with the center of the piece relative to the base/tip vector, if the angle is negative, the center of thickness is closer to the cutting edge, if it is positive, the center of thickness is closer to the back. The higher (or for negative angles: the lower) the angle is, the closer the thickness is located to the tip. A low distance from the center describes a thickness close to the center of the piece (about up to 0.2). A high distance from the center and low angles describe the thickness being closer to the base, whereas a high distance from the center and high angles describe the top 10% thickness being close to the tip

indicates that blanks where chosen for these tools that contain certain morphological features (e.g., a back opposite a sharp edge) which may fulfill comparable functional requirements. In contrast to Keilmesser, the artifact displayed in Fig. 12c has a larger area with high thickness. To the contrary, the other simple scrapers with a Keilmesser-like morphology show a variation in the extension of the thickest areas (see Supplementary Information Figs. 18–21). As, by definition, these tools are not shaped, this thickness patterning is caused by the morphology of the flake blank.

The four unifacially shaped scrapers with Keilmesser-like morphology lie within the variability of Keilmesser thickness distribution (Fig. 13), with the tendency that the thickest part is oriented towards the back. Like Keilmesser and simple scrapers with Keilmesser-like morphology, their thinnest areas are the cutting edge and the tip region (Fig. 12d), including the distal posterior part. Again, Thickness Mapping was able to detect morphological areas comparable to those of Keilmesser. Whereas for the simple scrapers with Keilmesser-like morphology this indicated a certain blank selection behavior, one surface of the unifacially shaped scrapers was shaped to create the distinctive tool morphology.

Although the Micoquian handaxes in our dataset (Fig. 12b) cluster within the variability of Keilmesser thickness distribution, they are different from the others as their thickest area is located exclusively within the base region and aligned with the center (Fig. 13) of the tool. In other words, they differ from the other tool types in having a more symmetric thickness distribution, which matches their more symmetric outline shape (see e.g., Fig. 10). This may indicate that they were shaped with the goal to create a more symmetric bifacial tool in contrast to the asymmetric Keilmesser. The handaxes form a tight cluster within the plot shown in Fig. 13, which still might be a result of their low sample size. The group is rather uniform compared to the others and the variation is mainly caused by the distance of the top 10% thickness from the center. The location of the thinnest areas is similar to the Keilmesser: the cutting edge, the tip and the distal posterior part, or, in the case of handaxes, the second, shorter cutting edge. Nevertheless, these results should be regarded with caution as there are only four or three artifacts (if one of them is instead a Keilmesser, see section about 3DGM results).

In conclusion, it has been shown that Thickness Mapping was able to trace the typological and techno-functional defined morphological parts on bifacial Keilmesser. The method confirmed the same morphological parts or areas on simple edge retouched and unifacially shaped scrapers with a Keilmesser-like morphology suggesting similar tool concepts that may fulfill comparable functional needs. Based on the Thickness Mapping, the handaxes of our dataset might be treated as a slightly different tool group with low variability in their thickness distribution. Their thickness is exclusively aligned with the center and concentrated in an area close to the base, suggesting a more symmetric tool concept.

Edge Angles

Figure 14 shows the variability of the edge angles computed from the 29 thickness maps along the cutting edge and the distal posterior part. Generally, the edge angles are variable along the analyzed edges of each tool type (Fig. 14a, b). This may be due to different states of edge retouch and reduction in which the individual artifacts entered the archaeological record. Different states of edge preservation, for example slight post-depositional edge damage on some artifacts that cannot be ruled out, might drive edge angle variability along the tool edges as well. For our analysis and comparison, we can neglect the latter as we focus more on general edge angle patterns and distributions than on absolute values. Additionally, as explained above, the angles were measured at a distance of 5 mm from the edge. At this distance the original angle of the edge is preserved and not affected by slight edge damage.

Keilmesser and the handaxes in this study show comparable edge angle distributions. Thereby, both tool types show no obvious difference between the edge angles of the distal posterior part and the cutting edge (Fig. 14). In other words, the active areas distal posterior part and cutting edge of Keilmesser and handaxes were not treated differently concerning sharpness. This indicates that, although the distal posterior part of Keilmesser is shorter than that of handaxes, the functionality of both tool types might be similar.

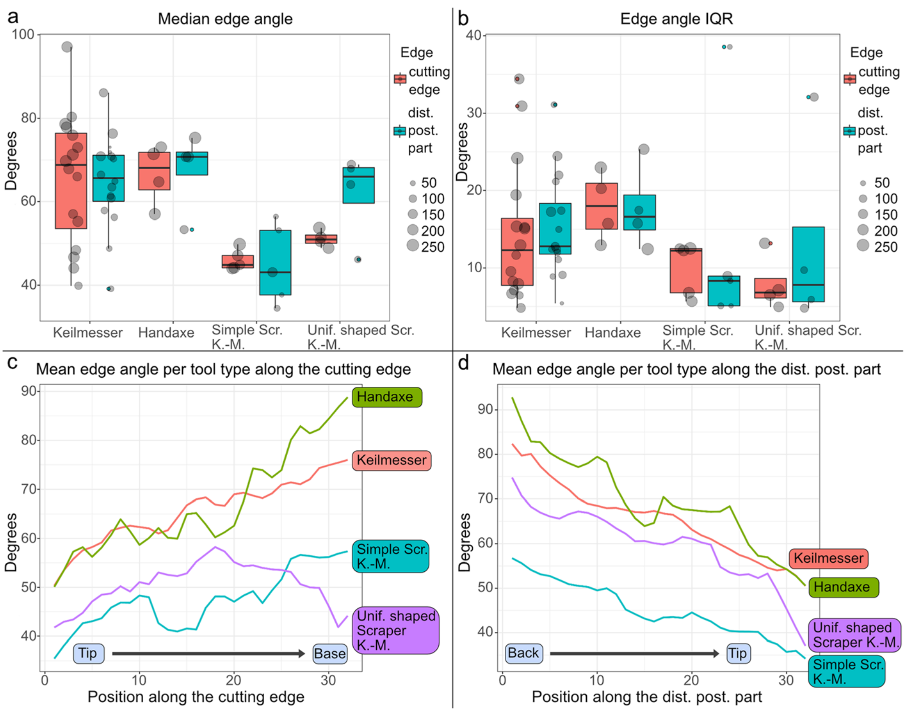

Fig. 14 Edge angles computed from the 3D models at semi-landmark positions located at distances of 0.5 mm (**a**, **b**) and at 30 equidistant semi-landmark positions (**c**, **d**) to a distance of 5 mm from each semi-landmark. **a** Boxplots illustrating the median edge angles of the cutting edge and the distal posterior part per tool type as well as the sample size per edge, gray circles mark the quantity of samples per edge (dependent from the length of the edge), note that filled red or green circles mark the outliers; **b** boxplots illustrating the interquartile range of edge angles of the cutting edge and the distal posterior part per tool type as well as the sample size per edge, gray circles mark the quantity of samples per edge (dependent from the length of the edge), note that filled red or green circles mark the outliers; **c** curves showing the mean edge angle per tool type along the cutting edge from the tip to the base; **d** curves showing the mean edge angle per tool type along the distal posterior part from the back to the tip

The edge angles of unifacially shaped and simple scrapers show a comparable pattern to the former tools (Fig. 14c, d), although their edge angles are generally much lower (Fig. 14a, b). The comparable edge angle patterns along the cutting edge as well as the distal posterior part suggest a functional similarity of the bifacial, unifacially shaped and simple edge retouched tools in our dataset. The lower edge angles of the latter two might be due to the intensity of retouch and blank selection, as the edges of the simple edge retouched and unifacially shaped scrapers are less retouched and reduced. Therefore, they are more dependent upon the original thickness of the flake blank as the more intensively retouched bifacially shaped Keilmesser and handaxes (see also the attribute analysis section). On the other hand, the edge angles of the distal posterior part of the unifacially shaped scrapers are rather high and comparably to those of Keilmesser and handaxes (Fig. 14a). This is the result of creating a steep striking platform for shaping on some of the unifacially shaped scrapers (see e.g., Fig. 1). In other words, the differences of average edge angle values between the tool types can be explained by differences in retouch and reduction intensities, or, in the case of unifacially shaped scrapers, edge functionality.

Despite the mean angles being variable along the edges of the individual tool types, they show comparable trends in all types suggesting similarities in active edge functionality (Fig. 14c, d). As expected from the morphology, thickness mapping, and typological criteria, the edge angles of all artifacts decrease towards the tip along both edges and increase towards the prehensile areas. The unifacially shaped scrapers with a Keilmesser-like morphology are an exception from this trend, as the angles of the cutting edge increase towards the center of the edge and increase not only towards the tip, but also towards the base. This is due to three of the four unifacially shaped scrapers having a rather narrow base with a cutting edge extending to the proximal part of the tool (see Figs. 1, 2; Fig. 4(2); 8d in contrast to Fig. 5(3)).

Attribute Analysis of the 29 Tools

Except for Micoquian handaxes, the PCA (Fig. 15a) shows a comparable picture for the variability of the tool types analyzed with 3DGM. Based on the attributes flatness, elongation, retouched to non-retouched edge length ratio or intensity of edge retouch, and the minimum and the maximum edge angle, handaxes fall clearly within Keilmesser variability. Thereby, handaxes form again a relatively tight cluster with low variation. The most different group, despite one overlap, is the simple scrapers with Keilmesser-like morphology. They are flatter, more elongated, have less intensely retouched edges, and show low edge angles (Fig. 15a, b; Table 4). As these attributes load predominantly on PC1 (Fig. 15b) and to some extent on PC2, the group of simple scrapers is moved to the upper right side of the PCA plot (Fig. 15a). Similar to the observations made for the 3DGM and edge angle analysis, the differences in these attributes in comparison to Keilmesser and handaxes can be explained by simple scrapers being flake tools, whereas the former were predominantly produced on flint nodules or natural flint pieces. As for simple edge retouched tools, no shaping took place and the edges are less retouched. In other words, the morphology of the original flake blank is only slightly altered. This results in flat tools with low edge angles (Table 4, Fig. 14). Therefore, it can be inferred that the differences between Keilmesser and handaxes on the one side and simple scrapers with Keilmesser-like morphology on

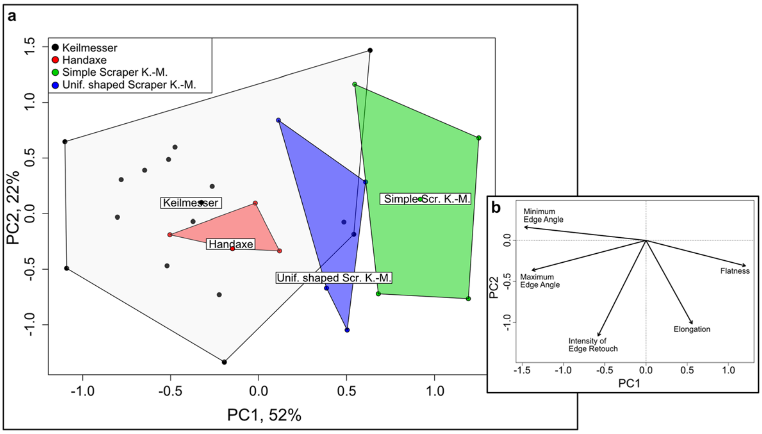

Fig. 15 PCA of 29 tools. **a** Principal component analysis of the Keilmesser, handaxes, simple edge retouched, and unifacially shaped scrapers with Keilmesser-like morphology analyzed with 3DGM and Thickness Mapping. Included are the attributes flatness, elongation, retouched to non-retouched edge length ratio or intensity of edge retouch, the minimum and the maximum edge angle. The group labels mark the spatial median of each group. **b** Directions of the loadings of each variable on PC1 and PC2

the other are mainly a matter of blank selection and retouch intensity. This hypothesis is reinforced by the position of the unifacially shaped scrapers with Keilmesser-like morphology. Their variability is close to the group of simple scrapers but overlaps as well with the variability of Keilmesser. Their shaping leads to more intensively retouched edges as observed on simple scrapers (Table 4), but with their morphology being still influenced by the presumably relatively thin flake blank, they still keep rather low edge angles and a moderate flatness compared to Keilmesser and handaxes (Table 4).

In conclusion, when the tools are analyzed using the mentioned attributes, Keilmesser have the highest variability within our dataset. Micoquian handaxes form a tight group within Keilmesser variability and have the least variation. Still, this might be the result of low sample size of handaxes. Keilmesser and handaxes share major similarities related to edge retouch and/or blank selection, e.g., thickness, edge angles, and edge retouch intensity. This trend can be followed over unifacially shaped scrapers through to simple edge retouched scrapers. The latter are the less edge retouched artifacts, influenced the most by the original flake blank in terms of flatness and edge angles.

Attribute Analysis of the Extended Dataset of 163 Tools

In the last step of our analysis, additional attribute data of Keilmesser, handaxes, and simple edge retouched and unifacially shaped scrapers with Keilmesser-like morphology are added to the PCA (Fig. 16). Furthermore, other typological tool classes are included in the analysis (Table 2, Table 4) to have a better impression of how their variability is related to the variability of the tool concepts targeted in this study. Included in this PCA (Fig. 16) are the same variables as for the PCA described above (Table 4). Because substantial group overlap obscures visibility in this case, only the spatial medians for the individual groups are displayed.

Table 4 Median values for the attributes used for the PCAs of 29 and 163 tools. High values for elongation = more elongated; high values for flatness = flatter; a value of 1 for intensity of retouch = all edges are covered by retouch

Tool type	*n*	Median elongation	Median flatness	Median intensity of edge retouch	Median max angle	Median min. angle
Sample of 29 tools						
Keilmesser	16	1.46	2.39	0.7	62.5	47.5
Handaxe	4	1.56	2.6	0.74	57.5	37.5
Scraper K.-M.	5	1.79	3.87	0.49	35	20
Unif. shaped scraper K.-M.	4	1.57	3.15	0.71	40	27.5
Sample of 163 tools						
Backed knife	7	1.44	5.09	0.5	41	27
Bifacial point	3	1.3	2.86	1	60	35
Bifacial scraper	8	1.61	3.04	0.46	62.5	49
Edge retouch	9	1.56	3.88	0.26	45	30
Faustkeilblatt	4	2.02	3.36	0.89	68.5	46.5
Handaxe	12	1.42	2.6	0.66	62.5	45
Keilmesser	32	1.47	2.43	0.69	63	45
Leaf. scraper	14	1.8	3.75	1	55	40
Simple scraper	40	1.44	4.14	0.39	48.5	35
Simple scraper K.-M.	5	1.79	3.87	0.49	44	28
Unif. shaped scraper	15	1.53	3.22	0.71	50	35
Unif. shaped scraper K.-M.	4	1.57	3.15	0.71	44	30
Use-wear	10	1.43	3.95	0.22	37.5	23.5

The attribute loadings for the principal components are similar to the PCA on the 29 tools analyzed by 3DGM and Thickness Mapping (Fig. 16). The edge angles and the ratio describing flatness load mostly on PC1, whereas the intensity of retouch and elongation load mainly on PC2.

The first observation that can be made is that two larger groups of tools can be differentiated. One cluster in the upper right of the plot (Fig. 16) contains formal simple edge retouched tools, like scrapers and backed knives. The artifacts of this first cluster are rather thin, less elongated and have the lowest edge retouch values (Table 4). The second larger group stretches from the upper left to the lower right and contains all of the unifacially and bifacially shaped tools, but also the simple edge retouched scrapers with Keilmesser-like morphology. This means that the latter are more related to the shaped "Micoquian" tools than to other formal simple edge retouched tools. They are separated from the formal tools of the first cluster by being more elongated and having a higher retouch intensity (Table 4). The main difference to the other Micoquian tool types is their flatness and their low edge angles (Table 4). As explained above, this is mainly caused by being manufactured on rather thin flakes with less invasive edge retouch.

The variability in the attributes of Keilmesser and handaxes is again closely related, illustrated by neighboring spatial group medians. This confirms the results of the PCA

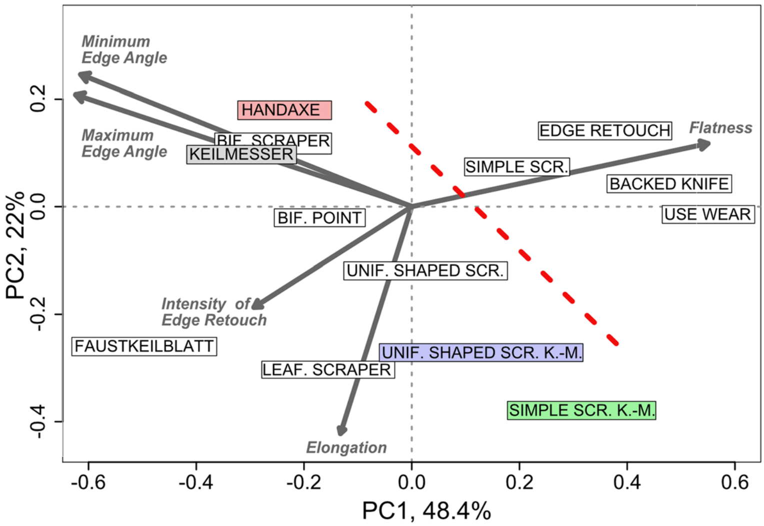

Fig. 16 Principal component analysis of the tools included in the 3DGM and Thickness analysis, as well as additional tools where attribute data was available and other late Middle Paleolithic tool types from the analyzed assemblages (Table 2). Included are the attributes flatness, elongation, retouched to non-retouched edge length ratio or intensity of edge retouch, and the minimum and the maximum edge angle. The group labels mark the spatial median of each group. Arrows illustrate the directions of the loadings of each variable on PC1 and PC2. The dotted red line illustrates the separation of Micoquian and shaped tools from formal simple edge retouched tools. For the plot showing the position of each individual artifact, see Supplementary Information Fig. 39

of the 29 initial artifacts included in this study. This is especially interesting, as in the present PCA there are more handaxes included (Table 2) than in the initial PCA (Table 1) of the 29 pieces. This is evidence of a stable and related variability pattern for both tool types. In terms of edge angles and elongation, they are also closely related to bifacial scrapers (Fig. 16, Table 4), a rather amorphous group of bifacial tools (Debénath and Dibble 1994).

Bifacial points and formal unifacially shaped scrapers lie on the edge angle trajectory (Fig. 16), differing mainly from Keilmesser, handaxes, and bifacial scrapers in having lower edge angles, at least concerning the minimum edge angle (Table 4). *Faustkeilblätter* and leaf-shaped scrapers plot in the lower left of the PCA plot (Fig. 16). They are the most elongated tools and have the highest intensity of edge retouch values. This was expected as the two tool types have several retouched working edges, but also blunted edges with a steep retouch that serves as a striking platform for shaping.

In conclusion, Keilmesser, handaxes, and bifacial scrapers are related when considering their flatness, elongation, rather steep edge angles and moderate edge retouch intensity in comparison to other Micoquian tools. Unifacially shaped and simple scrapers with Keilmesser-like morphology tend to be more related to shaped Micoquian tools than to other formal tools. This is because their edges are more intensively retouched, and they tend to be more elongated than other flake tools in our dataset. The main differences to the other shaped Micoquian tools are a higher flatness and lower edge angles, caused by being manufactured on potentially rather thin flakes.

Discussion and Conclusions

We applied a set of four different quantitative analytical methods, namely 3DGM, Thickness Mapping, edge angle analysis, and attribute-based PCA, on a sample of 29 late Middle Paleolithic Keilmesser, unifacially shaped and simple scrapers with Keilmesser-like morphology and Micoquian handaxes. We specifically chose tools that share similar morphological parts but that are typologically distinct due to blank type, the presence/absence of bifacial retouch, and symmetry. Our aim was to demonstrate, in a quantitative way, how variability within and between these tool types is structured, to investigate whether they have the potential to share a comparable functionality, and to know whether they then could be based on a single tool concept. Additionally, we performed PCA on an enlarged sample of 163 varied late Middle Paleolithic tool types to analyze the above-mentioned tools in a broader context. The artifacts come from a single region with the same paleoenvironment: a braided river system providing access to large-sized, high quality raw materials. The artifacts belong to an excavated assemblage and to surface collections recovered directly from sediments coming from the base of the last glacial fluvial sequence of the river Mulde. With the presentation of new luminescence dates in our study, we can show that the artifacts derive from the same chronological time frame of roughly 55 to 40 ka.

Variability Within the Dataset

We observed different, but closely related, aspects that structure variability which we attribute to variation driven by function/prehension connected to retouch intensity and shaping, by blank selection, and by our classification or typological systems.

The first major aspect of variability seems to be caused by shaping and stages of edge retouch and reduction connected to function. This resulted in varying outline shapes of the individual tools in the 3DGM results. Instead, similar treatment and reduction of the edges, inferred from the PC1 mean shape variation and the edge angle patterning, could be interpreted as a result of comparable edge functionality (e.g., Iovita 2009, 2010, 2014). The thickness distribution has further shown that there might be variation in bifacial tool shaping, resulting in asymmetric (Keilmesser) and symmetric (handaxes) bifacial tools. Shaping, retouch quantity, and retouch intensity also influence the variability we see in the attribute PCA where, for example, less intensively retouched flake tools have lower edge angles than more reduced shaped tools.

The second aspect of variability that we could observe in our dataset is variability structured by blank type. This variability separates the simple edge retouched and/or unifacially shaped flake tools from the bifacial core tools. This is especially the case for the edge angle analysis, the principal component analysis of attributes and, in the case of simple scrapers with a Keilmesser-like morphology, for the 3DGM analysis.

The third major factor causing variability is a variability patterning influenced by our classification system and in how we look at those pieces. Is a unifacially shaped tool with a Keilmesser-like morphology a scraper because just one side is shaped? How long must the distal posterior part be to separate a handaxe from a Keilmesser? Does the range of variability of bifacial Keilmesser represent different types of tools? Or is the underlying functional concept, the combination of the components base, back, cutting edge, tip and distal posterior part more important for the definition than the variability that we observe in the overall morphology of these tools?

In the following, we discuss how these aspects of variability can be interpreted and how they could help us to better interpret and understand the concepts underlying the tools in the dataset of our study.

Variability in Bifacial Keilmesser

Keilmesser are understood as a highly standardized tool type in their functional components and their shaping sequences (e.g., Jöris 2006, 2012; Veil et al. 1994). On the other hand, Keilmesser are interpreted as being highly variable in overall shape (Jöris 2006, 2012), which is confirmed by our finding showing this to be the tool group with the largest variability in all the methods we applied. To address this, some have created sub-types of Keilmesser based on their outline (Bosinski 1967; Jöris 2006: Fig. 6, 2012; Wetzel and Bosinski 1969). These sub-types are named after well-known sites where they were found: (1) the *Bockstein Keilmesser* with the back extending to the distal tip and a straight cutting edge, (2) the *Klausennische Keilmesser* with a more rectangular shape, a straight cutting edge parallel to the back and a straight distal posterior part, (3) the *Balver Keilmesser* with the back located at the distal posterior part, a straight cutting edge, and a bifacially shaped base, (4) the *Buhlener Keilmesser* with a more triangular shape and a straight cutting edge, (5) the *Pradnik-messer* having a circle segment shape with a rounded distal posterior part and a straight cutting edge, (6) the *Lichtenberger Keilmesser* with a rounded shape and a convex cutting edge, and (7) the *Königsaue or Wolgograd Keilmesser* with an elongated shape, a rather short proximal back, an extended distal posterior part with a pronounced, leaf-shaped tip and a convex cutting edge. Some of the Keilmesser in our dataset might match some of these sub-types (e.g., *Lichtenberger Keilmesser* Fig. 5(2) and Fig. 6(2)). Others in our dataset would require new sub-types (see e.g., the flat, round Keilmesser displayed in Fig. 4(1)). However, Jöris (e.g., 2006, 2012) has noted that metric analyses show much overlap between these types and that variability in shape might be due to the shape of the blank or blank type (e.g., flake, flint nodule, or flint slab). Additionally, shape variability has also been looked at as a result of different stages of reduction and subsequent resharpening of artifacts prior to entering the archaeological record (e.g., Iovita 2010, 2014, Jöris 2001, 2006; Migal and Urbanowski 2006; Urbanowski 2003). For Jöris (e.g., 2006, 2012), all this variation should be summarized under one concept or category, the *Keilmesser-concept*, where a back opposite a sharp (cutting) edge is the most important criteria.

Other factors that are seen to drive variability in Keilmesser, but will not be discussed here in detail, are esthetics (Veil 1995; Veil et al. 1994), distinct Neanderthal groups (Ruebens 2013, 2014), or chronological change (e.g., Bosinski 1967; Jöris 2004). At least the latter can be ruled out for our dataset, as the artifacts come from a similar early MIS 3 timeframe.

The Keilmesser-Concept and Typology

Our results show overlap in the variabilities of Keilmesser, unifacially shaped and simple scrapers with Keilmesser-like morphology and Micoquian handaxes. With the application of Thickness Mapping and subsequent edge angle analysis, we could show that similar active and prehensile areas as defined for the Keilmesser are contained as well within the morphology of the studied simple edge retouched and unifacially shaped scrapers. Our results suggest that in some instances whether a tool is typed as a Keilmesser, a scraper, or a Micoquian handaxe can be problematic and has the potential to be rather arbitrary and subjective.

Keeping in mind the small sample size in relation to their typological diversity in the late Middle Paleolithic, the Micoquian handaxes form in all our methods a rather tight cluster compared to the other groups. In other words, we could show in a quantitative way the separation of handaxes from Keilmesser. Concerning 3DGM, they have the longest distal posterior part, together with a more symmetric tip, of all artifacts and fall, therefore, mostly outside the variation of Keilmesser. This elongated distal posterior part or second cutting edge as well as a symmetrical thickness distribution gives the analyzed Micoquian handaxes a tendency to a more symmetrical shape. In contrast, regarding flatness, elongation, edge angles, edge retouch intensity, and thickness distribution, they form a rather tight group within the variability of Keilmesser. Additionally, they show a stronger relation to Keilmesser (and bifacial scrapers) for these attributes than to other late Middle Paleolithic tools. The analysis of the edge angles based on the thickness maps could show that Keilmesser and handaxes show comparable edge angle values and distributions along the distal posterior part and the cutting edge. This suggests that both edges were shaped and treated in a comparable way on both tool types. Therefore, the Micoquian handaxes of our dataset should be considered as distinct, more symmetric tool type, but that still lies within the range of Keilmesser variability. Our results for the Micoquian handaxes remain to be confirmed with a larger sample.

On the other hand, unifacially shaped scrapers with a Keilmesser-like morphology could potentially be considered as a variant of Keilmesser. They are the tool group most closely related to the latter in our analysis. Unifacially shaped tools fall within the shape and thickness distribution variability range of Keilmesser. Differences in edge angle and flatness seem to be related only to the flake blank. Additionally, they share the same flaking and modification sequences as bifacial Keilmesser (Fig. 1, Supplementary Information Figs. 30–38). As mentioned earlier, that Keilmesser can be (partly) shaped flake tools has already been suggested by Jöris (2006, p. 295): “Not all *Keilmesser* are true core tools; they can also be manufactured from flakes that have been more or less completely retouched over both surfaces.” When Pastoors (2001) assigned the late Middle Paleolithic tools to groups based on their shaping biographies and techno-functional units, some of his categories combine as well Keilmesser and scrapers (e.g., “Werkzeuggestalt 12”, Pastoors 2001, pp. 154–155).

Simple scrapers with a Keilmesser-like morphology show a low edge retouch intensity and their variability is mainly caused by the flake used for their production. This results in the simple edge retouched scrapers with Keilmesser-like morphology falling outside the variation of Keilmesser regarding most of the analytical methods we applied here. Therefore, it might be possible to interpret them as a separate tool category. On the other hand, they share (1) the components, (2) comparable flaking sequences (Fig. 1, Supplementary Information Figs. 30–38), (3) potential functionality inferred from the location of prehensile and active zones, as well as from the comparable treatment of the latter expressed in the PC1 shape change (Fig. 11) and comparable edge angle patterns, and (4) a similar blank selection behavior with Keilmesser, where a sharp edge opposite an already existing blunt back (naturally backed) seems to be the most important feature (e.g., Jöris 2006; Veil 1995; Veil et al. 1994). The PCA of the enlarged dataset has also shown that this type of scraper tends to be more related to the shaped Micoquian tools than to other formal scrapers. From this perspective, the simple scrapers with a Keilmesser-like morphology might be considered as a simplistic variant of the Keilmesser-concept, where all the functional requirements are, despite a few modifications, already fulfilled by the blank.

The question that arises from our results is why they made bifacial Keilmesser if they could fulfill their functional needs in different and simpler ways. The methodology applied in this study is not able to fully answer this question, but our results may point to some explanations. The inferences here can only be drawn from the assemblage of Pouch, as it is the only excavated assemblage in our dataset. A potential hypothesis might be technological traditions related to different human groups (e.g., flake tools vs. bifacial tools). For the assemblage of Pouch, we can most probably rule out this idea as bifacial Keilmesser and simple edge retouched/unifacially shaped scrapers with a Keilmesser-like morphology are part of the same assemblage. Another explanation for the different realizations of the Keilmesser-concept might be raw material characteristics and blank selection behavior. As reported by Veil (1995, 1994) for the site Lichtenberg/Lower Saxony, Germany, natural blanks that already contained morphological features within their morphology that may serve as prehensile parts were selected for the production of bifacial Keilmesser. Similar to that, large flakes with natural backs could be obtained in Pouch from large-sized raw materials, which were used for the production of the simple edge retouched and unifacially shaped scrapers with a Keilmesser-like morphology. A third explanation for applying the Keilmesser-concept to different blanks might be reduction and resharpening (Iovita 2009, 2010, 2014) in relation to a supposed long life of Keilmesser (e.g., Jöris 2001; Migal and Urbanowski 2006; Urbanowski 2003). That this is a probable explanation for the blank differences within our dataset has been shown by our multivariate analysis. We could show that differences in edge angles and flatness between simple edge retouched/unifacially shaped scrapers with a Keilmesser-like morphology and bifacial Keilmesser may be related to retouch intensity. The observed variation of this attribute might indeed be related to subsequent or continuous reduction and resharpening processes. This follows as well from the fact that two out of three Keilmesser from Pouch were manufactured on flakes and that some of the unifacially shaped and simple scrapers with Keilmesser-like morphologies bear the beginnings of one-sided shaping or bifacial shaping respectively (Fig. 1). Figure 1 and Supplementary Information Figs. 30–38 show as well that certain surfaces and edges were treated and modified in a comparable way on those tools, based on the same knapping sequences. Thereby, the thinning of the distal part or tip seems to be important. For this distal thinning, the distal posterior part was often prepared as a striking platform. This hypothesis is supported by the fact that the edges show comparable edge angle distributions (Fig. 14) despite their different states of reduction or retouch intensity. We can infer, therefore, that the edges were treated and modified following the same pattern or "template." Similar reduction strategies are also demonstrated by our 3DGM result, where the mean shape variation in PC1 (Fig. 11) is related to shape change in the longest cutting edge as well as the distal posterior part. In summary, we have evidence from the regional material analyzed in this study that differences in the realization of the Keilmesser-concept may partly be explained by blank selection and the state of reduction in which the artifacts entered the archaeological record.

The Keilmesser-Concept and Functionality

If we accept the concept of the Keilmesser as a flexible tool type or tool category rather than being exclusively valid for bifacial tools, then it can be defined as tool which is highly variable in shape and in the underlying blank but standardized in its components, or active and prehensile parts respectively. In this view, function is given the main importance for the realization of this concept during tool manufacture.

Although the 3DGM result demonstrated an outline shape variability to varying degrees between and within the tool groups, the main variation (PC1) of the mean shapes (Fig. 11) points to comparable edge modification and/or resharpening patterns for the active edges. Thus, we can infer a comparable functionality of these tool components (Iovita 2009, 2010, 2014). If we would further interpret the relationship between simple edge retouched, unifacially shaped, and bifacial tools as a continuum of resharpening (Fig. 1), we can see a tendency towards an allometric shape change from more elongated simple scrapers to a variety of shapes in the unifacially shaped and bifacial tools. But if the shape change of the single components is considered only (Fig. 11**)**, a tendency towards isometric shape change of the individual edges is visible. Thus, we can confirm the observations made by Iovita (2010; see also Jöris 2001) for the bifacial Keilmesser of Buhlen as outlined earlier. As the single morphological and functional components are retained, and already intentionally modified in the case of the simple edge retouched scrapers (Fig. 1, Supplementary Information Figs. 30–38), we can infer that the specific shape and the relationship between the components was functionally important for the knapper and needed to be retained during reduction.

On the other hand, a possible variation in overall tool function may be inferred from the varying location of the active and prehensile parts and the tool symmetry. If we follow the previous made suggestions about the functionality of bifacial Keilmesser (e.g., Jöris 2001, 2006, 2012; Richter 1997; Veil 1995; Veil et al. 1994), we can infer that the Keilmesser, unifacially shaped and simple scrapers with a Keilmesser-like morphology, as well as the Micoquian handaxes, served as cutting tools. Veil (Veil et al. 1994) interpreted the cutting tools in question as knives, based on use-wear analysis as well as their standardized, convex cutting edges. He interpreted differences in the shapes and the extensions of the cutting edge(s), as well as varying symmetries of the tip and the overall pieces as distinct shape concepts that may have served for different cutting purposes. Applying Veil's interpretation (Veil et al. 1994) to our dataset, his interpretation might be correct for Micoquian handaxes in contrast to Keilmesser, with the former having a prolonged and more symmetric, sharp distal part as well as a more symmetric thickness distribution that moved the prehensile part more towards the base. On the other hand, the simple edge retouched scrapers, the unifacially shaped tools as well as the Keilmesser analyzed in our study may represent a single functional tool concept as the prehensile and active zones are located at the same positions in an asymmetric way.

The Keilmesser-Concept as Type Fossil

The Keilmesser is the type fossil of the central and eastern European late Middle Paleolithic Keilmessergruppen. A recent quantitative study has shown that assemblage variability and classification within the central European Micoquian cannot be made with type fossils alone (Weiss et al. 2017) and that groups established by the presence or absence of type fossils can share aspects of variability and similarities on an assemblage level. These findings are in accordance with the earlier proposition of a "Mousterian with Micoquian Option" by Richter (Richter 1997, 2000, 2002, 2012, 2016). In a nutshell, he suggests that the bifacial component of assemblages that are indistinguishable based on their unifacial component varies due to occupation duration in a certain landscape and site function (among other factors). That it is problematic to define and characterize archaeological entities based on type fossils only has been well shown, e.g., for the Aterian of north Africa (Dibble et al. 2013) or the Lower/Middle Paleolithic transition in Europe (Monnier 2006), among other studies (see e.g., Monnier and Missal 2014; Shea 2014 for more on this topic). Nevertheless, Keilmesser and, given the results of the present study, the *Keilmesser-concept* applied to simple edge retouched and unifacially shaped tools are important characteristics of the central and eastern European Micoquian. It should, therefore, not be the exclusive but rather an inclusive characteristic of the central and eastern European Micoquian. Within the framework of future research, it might be interesting to compare this concept again to the handaxes that are the type fossil the MTA of western Europe. Previous research suggests that they were as well cutting tools, consisting of a prehensile part opposite a sharp cutting edge and a tip (e.g., Claud 2012; Soressi 2002; Soressi and Hays 2003). They possess an underlying concept of symmetry as well, formed by two convergent cutting edges—something that is also found on the handaxes in our dataset. It would be interesting to know whether they share more similarities than their main difference: plano-convex shaping in the case of Keilmesser (e.g., Jöris 2006, 2012) and biconvex shaping in the case of MTA handaxes (Soressi 2002).

The Keilmesser-Concept—Conclusion

With the application of 3DGM, multivariate analysis as well as Thickness Mapping and edge angle analysis, we could show in a quantitative way that morphological and functional components typical for late Middle Paleolithic Keilmesser can similarly be found on simple edge retouched and unifacially shaped tools. Despite variability related to classification and typology, blank selection, shaping, and retouch intensity, the tools are composed of similar functional/morphological units to fulfill the functional requirements of prehensile and active zones. These units or components are defined under the *Keilmesser-concept*: a prehensile base and a natural and/or partly retouched back, opposite a sharp edge and a modified tip. A second sharp edge, the distal posterior part, might be adjacent to the back, converging with the cutting edge at the tip. Despite some minor differences caused by being flake tools with only one-sided shaping, the unifacially shaped scrapers of this dataset are the most similar group of tools to the bifacial Keilmesser. Therefore, they should be regarded as a unifacial variant of the latter. The simple scrapers with Keilmesser-like morphology can be interpreted as a special simplistic variant of Keilmesser, where the blank already fulfills the functional requirements, although this interpretation has to be verified by a larger dataset. As the tools analyzed here show strong relations regarding their morphology and their active and prehensile zones, as well as a potential isometric shape change of the active parts during reduction, we can potentially infer that they share a comparable functionality. In our dataset, differences concerning the realization of the Keilmesser-concept as bifacial, unifacially shaped, and simple edge retouched tools might in part be caused by raw material and blank selection, as well as being the representation of a continuum of reduction and resharpening. Therefore, our results suggest a more flexible late Neanderthal tool manufacture and tool use behavior than our rather strict typological distinctions may imply.

Some additional results were obtained for the relationship of Micoquian handaxes and Keilmesser. Although in the range of the Keilmessser-concept variability, handaxes are somewhat different in shape and symmetry and might form a separate but functionally related tool. Keeping in mind the low sample size of Micoquian handaxes in our dataset, they appear to be a special, more symmetric form of Keilmesser—at least in our dataset. Due to the low sample size of the Micoquian handaxes relative to their morphological diversity within the late Middle Paleolithic across Europe, these results need further investigation. Additional analysis of an enlarge dataset may show whether the Micoquian handaxes are indeed a special, separate tool category, or if the prolonged distal posterior part and the shorter back is just the result of further shaping, with the back used as a striking platform.

Here we demonstrated with a set of analytical methods morphological and functional similarities and differences between the tools in our dataset. Based on this initial result, the sample size will be expanded in the future to learn more about how variability in late Neanderthal toolkits is structured.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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