Typo-chronology for the Mesolithic between 9000 and 7800 cal BC in Central Europe: a new approach to use constrained correspondence analysis (CCA) of microliths for dating

Typochronologie für das Mesolithikum zwischen 9000 und 7800 cal BC in Mitteleuropa: ein neuer Ansatz zur Datierung unter Verwendung der kanonischen Korrespondenzanalyse von Mikrolithen

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Abstract
Microlith types are of crucial significance for relative dating of Mesolithic assemblages as well as for assigning them to cultural traditions. This is especially important for assessing inventories from surface collections and old excavations. Here we present a new way of multivariate analysis to relate microlith type spectra to chronology. Our data set comprises 34 radiocarbon-dated microlith assemblages from Germany and the BeNeLux region dating to the Early Mesolithic and the early Middle Mesolithic (c. 9000 to c. 7800 cal BC, i.e. later Preboreal to early middle Boreal) as well as two radiometrically undated assemblages. The typological classification of the assemblages is submitted to a constrained correspondence analysis (CCA) using calibrated radiocarbon age of assemblages (cal BC) as a constraint. As an innovation we apply a so called calibration of the CCA model – not to be confused with calibrating radiocarbon dates (!) – to estimate the cal BC dates for the two assemblages which had no specific dating information. Besides the canonical chronological ordering of the assemblages the CCA triplot also shows interesting features related to geographical regions and cultural traditions, which require further investigations.

Keywords
Early and Middle Mesolithic, north western Central Europe, typology of Mesolithic microliths, C^{14}-dating, CCA (constrained correspondence analysis), CCA calibration model

Zusammenfassung
Mikrolith-Typen sind sowohl für die relative Datierung mesolithischer Inventare als auch für ihre Zuordnung zu kulturellen Traditionen von größter Bedeutung. Sie sind besonders wichtig für die Beurteilung von Inventaren aus Oberflächenaufsammlungen und Altgrabungen. Hier stellen wir eine neue Art der multivariaten Analyse vor, um Spektren von Mikrolithtypen mit der Chronologie in Beziehung zu setzen. Unser Datensatz umfasst 34 ^{14}C-datierte Mikrolithkomplexe des Frühmesolithikums und des frühen Mittelmesolithikums (ca. 9000 bis ca. 7800 cal BC, d.h. mittleres Präboreal bis mittleres Boreal) aus Deutschland und der BeNeLux-Region sowie zwei radiometrisch undatierte Fundkomplexe. Die typologische Klassifikation der Mikrolithinventare wird einer kanonischen Korrespondenzanalyse (CCA) unterzogen, wobei das kalibrierte ^{14}C-Alter (cal BC) als Bedingung verwendet wird. Völlig neu ist die Anwendung einer sogenannten Kalibrierung des CCA-Modells – nicht zu verwechseln mit der Kalibration von Radiokohlenstoffdaten (!) –, um die kalibrierten BC-Daten für die zwei Mikrolithkomplexe zu schätzen, für die es bisher keine konkrete Altersbestimmung gab. Neben der kanonischen chronologischen Ordnung der Inventare zeigt der CCA-Triplot auch interessante Hinweise auf Zusammenhänge mit geographischen Regionen und kulturellen Traditionen, die weitere Untersuchungen erfordern.

Schlüsselwörter
Früh- und Mittelmesolithikum, nordwestliches Mitteleuropa, Typologie mesolithischer Mikrolithen, ^{14}C-Datierung, CCA (Constrained Correspondence Analysis), CCA-Kalibrierungsmodell

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Introduction

Microlithes are a phenomenon that we know mainly from the Mesolithic of Europe and the Epipaleolithic in Northern Africa. As shafted original finds and microwear analysis show, it can be assumed that they served as arrow heads, as lateral reinforcement of arrows or even as knife inserts.

Already in the early 20th century it was recognized that the variability of microlith forms can be interpreted chronologically and culturally. The basic consideration is that these are weapon or tool parts that were only used for a short period of time, which have not undergone any reworking after the first shaping and therefore – if they are not heavily damaged – the original shape can be assessed. Moreover, many retouched forms appear to be independent of the narrower function. It can therefore be assumed that these types, just like the way they are retouched, potentially follow inherited traditions and can thus provide indications of cultural identity. On the other hand, several archaeologists have questioned the effectiveness of typological studies given that the classification of artefacts can be arbitrary constructs which may differ depending on the respective researcher (Clarke 1968; Binford 1972; Clark 1992). The authors are aware of this bias. Nevertheless, combining radiocarbon dating with different microlith types does seem to indicate specific patterns which we will discuss in this paper.

Since the 1930s there have been numerous approaches to systematically describe microliths and define shapes and processing methods. The different systematic approaches of typology are not included here since they are beyond the scope of this paper. It is important to note that type collections usually refer to narrower geographical areas (e.g. Taute 1971; G.E.E.M. or Barriere et al. 1969; 1972; Gramsch 1973; Gob 1984; Petersen 1993). This is understandable, because although many microlith forms are similar over large areas, but in the details, especially regional peculiarities can be recognized.

The difference of microlith types has been interpreted mainly chronologically so far. There is a lot of evidence for the chronological relevance of microliths. In Germany, above all the stratigraphy in Friesack 4 (Brandenburg) and the Jägerhaus-Höhle at the upper Danube near Beuron (Baden-Württemberg), but also the settlement areas of Rottenburg-Siebenlinden (also in Baden-Württemberg) and Duvensee (Schleswig-Holstein), which exhibit several successive occupations and are more or less well dated, show that there are good reasons for this interpretation.

In addition to chronology, the geographical distribution of certain microlithic forms or processing techniques is also seen as an indication of cultural or traditional areas. Depending on whether one is looking at the whole of Europe or only a part of it, the results, which are usually presented using distribution maps, differ (e.g. Kozłowski 2009 for the whole of Europe; Czielsa 2015; 2016 for western Central Europe). Other studies refer to the identification of social territories (Gendel 1984; Spies 2020, this volume). We also believe that the composition of microlithic forms in specific find ensembles reflects cultural traditions that have been passed down through generations, and that these traditions can also be defined geographically. However, it will not be possible to identify cultural groups and their territories on the basis of microliths alone. Not only, that fixed borders are not to be expected in mobile hunter-gatherer societies, it is of course far too narrow a view to define cultural groups exclusively on the basis of microlith types which present only a small part of the cultural lives of Mesolithic groups. The gradual change in the type-appearances in the course of time probably reflects socio-cultural changes and adaptations to change in environmental conditions. Mathias Blessing, for example, deals with the development of microliths in North and South Germany in a comparative study on risk minimisation during the Early Mesolithic. He interprets the differences in type variability and artefact-dimensions during the Early Holocene as reactions of hunter-gatherer societies to the changing environment. It is said that increasing forestation in particular led to greater type diversity and smaller microliths (Blessing 2016).

But no matter which question is pursued in detail, without a reliable chronology as a basis, all efforts are fruitless. The basis of any investigation with the aim of reconstructing historical events is a chronology that is as valid and narrow as possible. A relative chronology forms the minimal grid to which a discussion of local courses of action and regional developments can refer. If this chronology is backed up and specified by radiocarbon data, one can come much closer to a story. However, the relatively few well-dated find ensembles are not sufficient to enable us to trace cultural developments, interactions between social groups or with the environment, reactions to climate events or population movements. This requires the important information contained in the thousands of Mesolithic surface assemblages containing microliths that are found in almost every region. If these are to be used for further research, a scientifically proven instrument is needed to classify them chronologically.

For some time now, multivariate statistics have been used to describe and chronologically interpret the similarities or dissimilarities of microlithic inventories of selected regions. More recently, the dissertation by Svea Mahlstedt (2015, 101 ff.) for north-western Lower Saxony and the master's thesis by Benjamin Spies for Lower Franconia (Spies 2016) deserve special mention. With the help of cluster and correspondence analyses with summarising type groups (micropoints, triangles, segments and some trapezoidal forms), S. Mahlstedt showed that although the inventories she examined were roughly chronologically sorted into an early and a late phase, a closer chronological classification was not possible. In contrast, B. Spies showed that a correspondence analysis of the microlith types according to W. Taute (1971) already showed a stronger differentiation, corresponding to his Beuronian phases A, B, and C and the Late Mesolithic. A similarly good chronological differentiation could be worked out by Jan Kuper for the Epipaleolithic of the Eastern Sahara by means of a transformation based principal component analysis (Kuper 2019, 214 ff.). As a basis he used Jacques Tixier's typology for the stone tools of the Maghreb (Tixier 1963). He included not only the microlithic forms, but also other distinctive types of tools such as end-scrapers and burins. However, only a few of them proved to be chronologically relevant, while the microlithic forms (geometric types and backed bladlets) produced clearer results, and certain microlithic forms could even be attributed a 'Leitform' character. Using this method, Kuper was able to make a chronological classification of the C^{14}-dated microlith-ensembles, the accuracy of which – depending on the phase and the number of valid radiocarbon dates respectively – lies between ca. 1200 and 400 years.

During the processing of the microlithes from the stratigraphy of Friesack 4 in Brandenburg within the framework of a project at the University of Cologne funded by the German Research Foundation (application Zi 276/13-1) (Gehlen 2008; 2010), an approach was developed which allows microlith inventories to be dated more accurately. At the suggestion of the project leader Andreas Zimmermann, a special procedure similar to a constrained correspondence analysis was applied, in which the sequence of stratigraphic units in the rows is determined by the radiocarbon dates and/or the stratigraphic position. In this way, 'Reciprocal Averaging' is used to quantitatively determine the position of each microlithic form in the columns and to calculate the similarity of the different inventories (the calculation is done in MS-Excel using a simple matrix calculation).

As a result of the Friesack project, Birgit Gehlen, Nele Schneid and Annabell Zander have supplemented the Friesack data with the microlith complexes of further C^{14}-dated inventories from the Mesolithic and the Final Palaeolithic. N. Schneid and A. Zander then successfully applied this method in their master's thesis and final papers on Mesolithic find ensembles from Westphalia. Schneid was able to describe the cultural position of the C^{14}-dated complex from Rieger Busch in Hagen between the contemporary Mesolithic groups in Northern Germany and those from the area of the todays BeNeLux states. She points to an important result of the microth analyses, namely that a geographical imbalance in the data basis can be seen in the diversity of the microlith types. In northern and north-eastern Germany, there are more dated significant find ensembles – among others from the particularly information-rich stratigraphy in Friesack 4 – while in southern Germany there are only two significant sites (if Rottenburg-Siebenlinden is considered as one find-area) with several microlithic inventories. This becomes clear from the fact that in the north specific types can be described in their distribution on a small scale (Friesack types), whereas the greater area of southern Germany does not show any forms of its own in the Early Mesolithic (Schneid 2014, 116 ff.; Schneid 2017). Zander was able to show that certain microlithic types of the Ahrensburgian represent cultural connections to the Long Blade complexes and the following Initial and Early Mesolithic in north-western Germany (Zander 2016a, 96 ff.; Zander 2016b). This method and some results are described in publications by B. Gehlen (Gehlen 2009; Koch et al. 2017).

Despite the promising results some shortcomings of this method are obvious. For one thing, each inventory to be dated had to be integrated into the existing matrix at the most appropriate location, which was time-consuming. This usually required multiple attempts and was also prone to errors due to manual copying. On the other hand, the chronological statement remained relatively imprecise depending on the time period. In addition, independent reproducibility is not ensured and there is also no option to safeguard against random chance due to sampling effects.

Sources and source criticism

The basis for the procedure presented here is a typology that offers comprehensible criteria for the naming of microliths. The types used here are described in **Appendix A**. The basis for the type definitions, which were created by B. Gehlen, Ingrid Koch, Anna-Leena Fischer and N. Schneid within the above mentioned research project on the flint material of Friesack 4, are on the one hand publications of other authors (Gramsch 1973; Taute 1971; Petersen 1993) and on the other hand the forms found in Friesack 4. Since the first version of 2007, the type list has been continuously extended, as new types were discovered in new fields of work, which had to be defined. It is an important task for the future to publish this classification as a whole and to make it accessible to all interested parties. The type list in **Appendix A** also includes – as far as possible – the definitions known from the Franco-Belgian region, which were published by the Groupe d'étude de l'Épipaléolithique-Mésolithique (G.E.E.M.) in 1969 and 1972 (Barrière et al. 1969; 1972) and have served for quite a long time as a basis for the type approaches in this area.

The application of the procedure proposed here obviously poses a number of problems. An essential basis is of course the precise application of type definitions in the recording of microliths. Although the type descriptions leave a certain amount of room for interpretation – there are, for example, only a few definitions that include absolute length and a certain amount of variation is permitted when estimating the dimensions of the retouched edges – interpretations by individual researchers have no place at this point. Unclear fragments and untypical individual forms are therefore not taken into account. Experience within our extended work group has shown, however, that the recording of microlith types is generally less prone to errors than one might imagine.

Many publications contain radiocarbon-data, but no type lists of the microliths of the dated ensembles and not necessarily representative drawings of the pieces. It must therefore be assumed that only a part of the data can be recorded and possibly an important part cannot be identified. Furthermore, there are relatively few C^{14}-dated find complexes. These radiocarbon-dates have often been made early (like e.g. those of the Jägerhaus-Höhle). At that time, only few so-called 'bulk-samples' were taken, which were conventionally dated and did not yield really precise data with often large standard deviations. In addition, laboratory methods have improved considerably over the last 50 years – the extent to which the respective preparation and measurement procedures of the different laboratories affect the data cannot be estimated.

It is therefore expected that the data basis presented here will be significantly improved in the future – both in terms of comparative dating and in the precision and completeness of artefact acquisition. Nevertheless, we assume that this will refine the results presented here, but not falsify them.

Research at the site Friesack 4 – the starting point for the following chronological investigation

The most complex stratigraphy of the Mesolithic-Neolithic bog site of Friesack 4 in Northeastern Germany is unique in Europe. From the Early Mesolithic (later Preboreal around 9000 cal BC) until the Late Mesolithic (early Atlantic around 5800 cal BC) hunter-gatherers visited repeatedly this part of the lakeside. Neolithic settlers lived there during the younger Atlantic period. More than 120 subaquatic archaeological layers in five sections contained about 140,000 Mesolithic and 18,000 Neolithic lithic artefacts as well as thousands of animal remains and organic finds. Friesack 4 was mainly excavated during the 1970s and the 1980s by Dr. Bernhard Gramsch (then *Landesmuseum für Ur- und Frühgeschichte Pots-*

dam), who already published ample information (see Cziesla & Witkowski 1999 and the list of publications by Bernhard Gramsch at the end of this book). The Friesack 4 site is most famous for its numerous bone and antler artefacts, part of them ornamented, and the remains of Mesolithic fishing nets and wooden implements. Until now from all trenches 93 C^{14}-dates by the Berlin and Cologne laboratories were measured.

The project ‚Die Feuersteinartefakte des mesolithisch-neolithischen Moorfundplatzes Friesack 4, Kr. Havelland, Brandenburg' was funded by the *'Deutsche Forschungsgemeinschaft'* (German Research Foundation) from 1st August 2005 to 29th Februrary 2007 (application A. Zimmermann/ Zi 276/13-1). During this first part of the project B. Gehlen worked out the stratigraphy by Harris-matrices and analysed the c. 3000 Mesolithic microliths and microburins from the site. This project was followed by a further one titled 'Die Feuersteinartefakte der mesolithisch-neolithischen Moorfundstelle Friesack 4, Lkr. Havelland (Land Brandenburg) – Stratigrafie, Formen, Technologie, Vergleich, Gebrauchsanalyse' (application Zi 276/13-2), in which B. Gehlen, Jaqueline Ruland and Alfred Pawlik completed the research on the flints from Friesack 4 and produced a huge documentation, whose preparation for publication is unfortunately not yet completed (Gehlen et al. in prep.).

After realising, that the correlation of the multiple layers from trench B with the trenches Z, A, C and D were problematic, the analysis of the flint material concentrated on the reconstruction of an ideal stratigraphic series with as much as significant and C^{14}-dated microlithic finds as possible. For that purpose, only the find material of the trenches Z, C and D have been analysed so far. Trench Z delivered the most informative and varied material; from trench C only the substrata from layer 23 and only the Late Mesolithic finds from trench D which are not of interest here, were included in the analysis. The stratigraphies of trench Z and layer 23 from trench C contain 122 findlayers, most of them with typologically identifiable microliths. In sum, 682 microliths are used in the following CCA. A first correspondence analysis using 'reciprocal averaging' of the microlithic types and their frequency after the stratigraphic sorting by a Harris-matrix led to a grouping of layers which probably corresponds to certain settlement periods. The former division of the stratigraphy in four Mesolithic complexes (I to IV) by Bernhard Gramsch (see Gramsch 2000; 2006; Görsdorf & Gramsch 2004) – confirmed by radiocarbon-dates and by pollen-analysis – was supported by this examination. Furthermore, these periods could be subdivided into 17 layer complexes, from which 10 are used for the research presented below. It is obvious by the C^{14}-dates that these subdivisions represent shorter chronological phases. This differentiation in several short chronological periods is most important for the general chronology of the Mesolithic in northern and north-eastern Germany.

The results of the typo-chronological examination of the Friesack 4 site show diversity in continuity. Results of the attribute analysis of these artefacts in context with the stratigraphies and the absolute chronology reveal a more or less continuous development from the later Preboreal to the early Boreal in terms of typology, style, the dimensions of microliths and micro-burins and the mode of blade technology (Gehlen et al. in prep.; see **Fig. 1**). But they also display the continuous introduction of new elements during time.

During the Preboreal the first narrow lancet points occur, which are very variable in early Boreal times. The lancet points are especially characteristic of the complexes III and IV in Friesack 4. It is very important that those types are absent in the Duvensee sites dated to the late Preboreal and early Boreal, and only rare in the middle Boreal site Duvensee 13. But they are frequent in the late Boreal and early Atlantic sites of Reichwalde (Oberlausitz) in southern Saxonia, dated between app. 6900 and 5900 cal BC (Vollbrecht 2001). It is probable that these slender microliths are typical for Mesolithic groups in the eastern part of Germany. Some types of micro points, lancet points and triangles has been also found in the Maglemose culture of Denmark. The very small number of characteristic microliths from the north reveal only very loose relationships of the earlier Mesolithic people at Friesack 4 and southern Scandinavia from the late Preboreal onwards until the early Boreal. But these relations must be studied closer in the future.

The Method

Why should one identify each and every microlith of an assemblage by type? Because the typological classification of an assemblage of micro-

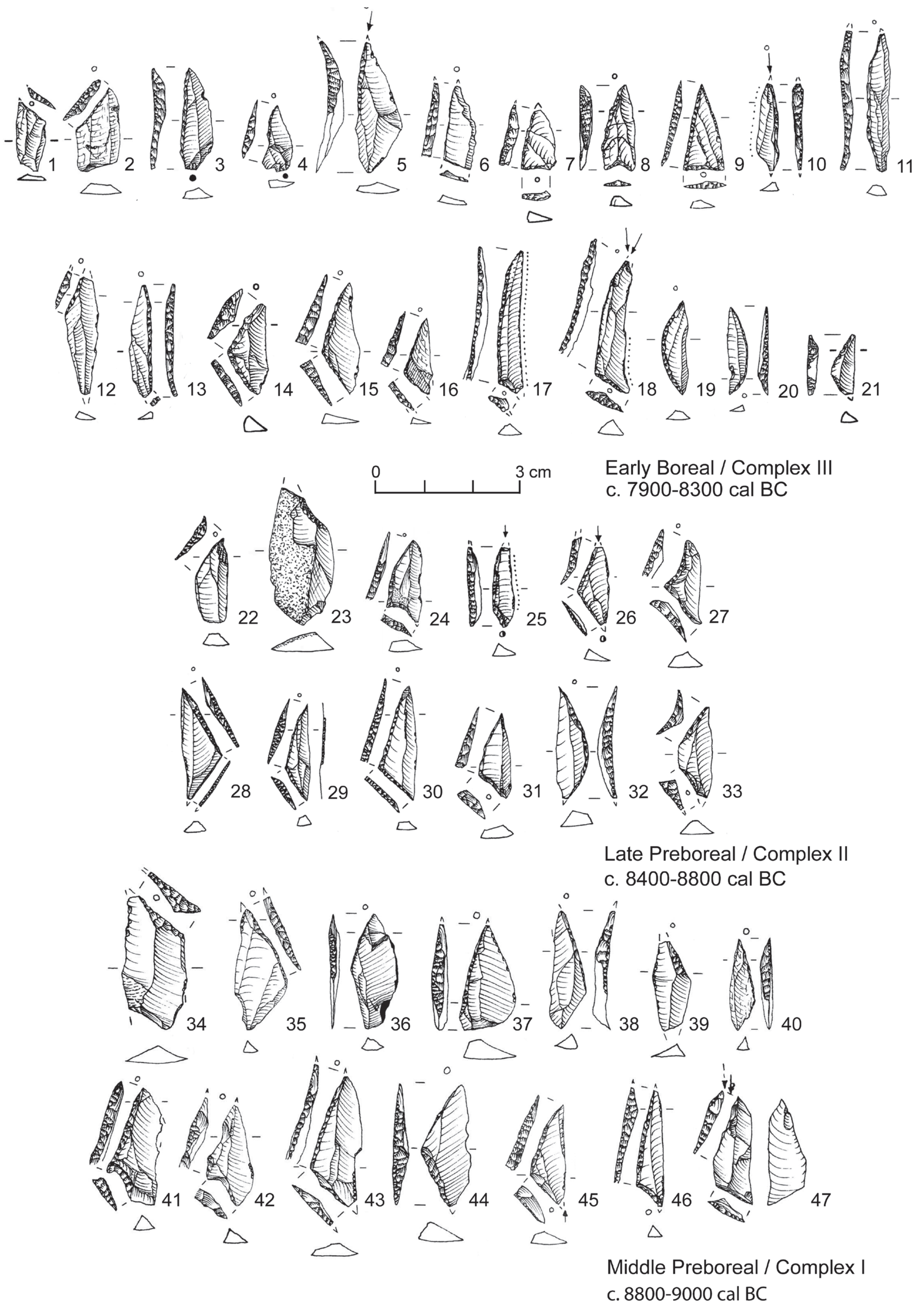
1 2 3 4 5 6 7 8 9 10 11
12 13 14 15 16 17 18 19 20 21
0
3 cm
Early Boreal / Complex III
c. 7900-8300 cal BC
22 23 24 25 26 27
28 29 30 31 32 33
Late Preboreal / Complex II
c. 8400-8800 cal BC
34 35 36 37 38 39 40
41 42 43 44 45 46 47
Middle Preboreal / Complex I
c. 8800-9000 cal BC

Fig. 1 (page 320) Microliths of the Early and Middle Mesolithic from the well-known site Friesack 4.
1-21 Early Boreal 1, 2 A020; **3, 4** C021; **5** C022; **6** C023; **7, 8** C025; **9** C027; **10** C031; **11** C033; **12** C037;**13** C039; **14** D011; **15, 16** D021; **17, 18** D025; **19, 20** E040; **21** F025.
22-33 Late Preboreal 22, 23 A020; **24** C029; **26** C036; **27** D011; **28** D014; **29, 30** D021; **31** D028; **32** E020; **33** F025.
34-47 Middle Preboreal 34 A020; **35** C010; **36-40** C022; **41, 42** C029; **43-45** D021; **46** D028; **47** F031
(drawings B. Gehlen, I. Koch and A. Rüschmann; scale 1:1).

Abb. 1 (Seite 320) Mikrolithen des Früh- und Mittelmesolithikums von der berühmten Fundstelle Friesack 4.
1-21 Frühes Boreal 1, 2 A020; **3, 4** C021; **5** C022; **6** C023; **7, 8** C025; **9** C027; **10** C031; **11** C033; **12** C037;**13** C039; **14** D011; **15, 16** D021; **17, 18** D025; **19, 20** E040; **21** F025.
22-33 Spätes Präboreal 22, 23 A020; **24** C029; **26** C036; **27** D011; **28** D014; **29, 30** D021; **31** D028; **32** E020; **33** F025.
34-47 Mittleres Präboreal 34 A020; **35** C010; **36-40** C022; **41, 42** C029; **43-45** D021; **46** D028; **47** F031
(Zeichnungen B. Gehlen, I. Koch und A. Rüschmann; M. 1:1).

liths can be considered to be a multivariate description of a complex phenomenon. It may encompass aspects of information related to space, e.g. regional traditions or indirect regional effects of vegetation on fauna and therefore – more indirectly – on hunting and its implements. It may contain information about technological choices and/or about hunting strategies and many more aspects. And all these may in turn be related to chronology. To relate one or more of these aspects to assemblage composition one requires several inventories, say, more than a dozen at least. And only if the relation is strong enough and there are enough assemblages one can unveil the relation between differences in typological composition and possible causal variables.

In technical terms, one needs a medium to large sized data table which comprises the multivariate typological description and the variable or variables assumed to be causal for – at least some aspects of – the compositions. The rows represent assemblages, or sites or any archaeologically reasonable entity, and the columns hold the counts for different types. Some of the last columns may hold those attributes of the assemblages which we consider to act causally on the compositions. The cells are integer numbers (counts) and may include zero. To put it even more simple, any data table where the part holding the counts can produce rows sums and column sums which make sense archaeologically may be used. Note, that such a setting is enormously flexible since it can practically hold any kind of data where compositions are represented by counts, starting by typologically described coin hoards and not ending with counting different topics painted by attic red figure vase painters or numbers of different animal species in rock paintings. With slight adaptions also binary resp. presence/absence data may be used instead of counts. For all these settings one may investigate the relation between the composition of an entity – represented by counts – and one or more attributes of the entity considered to be causal for the composition.

Here we strongly advice against intuitive approaches based on feeling and impression by just 'looking at the numbers' and 'recognizing phenomena by experience'. We instead, would like to emphasize the advantages of a straight approach based on quantitative tools and open software which allows computational reproducibility as well as replicability (Marwick 2017; for replicability see also explanations in our annotated R code in **appendix D**).

Methods to relate compositional information represented by multivariate count data with causal variables are covered by canonical ordination analysis in multivariate statistics. Basically three choices are possible, constrained correspondence analysis (CCA; ter Braak 1986), transformation based redundancy analysis (tbRDA; Legendre & Gallagher 2001; Borcard et al. 2018, 55) and distance based redundancy analysis (dbRDA; Legendre & Anderson 1999; Borcard et al. 2018, 249). Note, if only the causal relation between the counts of one microlith type and one or more attribute(s) of the assemblages is to be analyzed, generalized linear models for count data like quasi-Poisson models or zero-inflated Poisson models should be used (Friendly et al. 2014, 451 *passim*).

All three canonical ordination analyses solve the same task: relate multivariate data to so called constraining variables i.e. the variable(s) we assume to cause resp. to influence compositions, test this assumed relation against a null hypothesis of no relation and order the cases mainly according to that part of the dissimilarities between the compositions which can be expressed numerically by a formula only involving the constraining (causal) variable(s). The main difference between the three approaches is the way they measure the dissimilarity between compositions expressed as counts. Because a PCA basically preserves the Euclidean distance between cases (Legendre & Legendre 2012, 433), applying a base PCA to count data leads to the – in ecology – well known species abundance or Orloci paradox (Orloci 1978, 46), that is, dissimilarities are grossly distorted when the row sums are different. In 2002 Legendre and Gallagher developed transformation formulae which, when applied to count data, remove these distortions. Later their application within a PCA framework was called transformation based PCA (tbPCA). Its canonical version is transformation based redundancy analysis (tbRDA; Borcard et al. 2018, 204). Distance based redundancy analysis (dbRDA; Legendre & Anderson 1999) is just the combination of a principal coordinate analysis, a multiple regression and a PCA of the regression fits.

We apply CCA here mainly for two reasons, one technical and one methodological. The first is simply that a CCA preserves chi-square distance (Legendre & Legendre 2012, 665) which is appropriate for count data especially when columns with rare types should be weighted more heavily in the computation. The methodological one is also simple: unconstrained (simple symmetrical) correspondence analysis being one part of the CCA algorithm is well known in archaeology for decades (in Germany e.g. Müller & Zimmermann 1997). To confess, to varying degrees all of us are indeed indebted to the Cologne school of numerical archaeology as promoted by Andreas Zimmermann in the last decades.

But why all this fuss about the methods? Simply because choosing the correct method is paramount to any reliable scientific insight. And to elucidate the possible choices we inserted the above paragraphs. And while we do not want discuss the matrix algebra of CCA in detail – those interested find a superb presentation in the volume by Pierre and Louis Legendre (2012, 661 passim) – we would like to offer a metaphorical explanation of its working mechanism, spiced with a few numerical expressions just to not later confront readers with results out of a black box. A step by step explanation of a CA is presented in Michael Greenacre's excellent text 'Correspondence Analysis in Practice' (2017). The CA part first expresses counts as parts of the table sum, computes an average table of cell percentages, sometimes called expected values, and takes the difference cell by cell. These differences are then divided by the expected values, again cell by cell. One could say, the table was centered and scaled. Now think of the rows of the resulting table as points with the numbers in the cells representing the point coordinates. Such a point cloud may exist in 33 dimensions but the principles explained here work just as fine as if it were only three dimensions.

Here the canonical aspect of CCA steps in (Legendre & Legendre 2012, 665 passim). Each column of the scaled table is expressed by a weighted linear combination of the constraining variable(s) i.e. there is a weighted linear regression for each column onto the constraint(s), the weights being row sums of the cell percentage table. This amounts to say, from now on CCA can only work on that aspect of information embedded in the count data which can also be expressed by the constraining variable(s) i.e. it focuses on the causal relation. And we also get a numerical measure, called explained inertia, for how high the resemblance between the count information and the constraint(s) is i.e. a measure for the strength of the causal relation. Note, while technically seen, explained inertia is not just another version of the coefficient of determination, R squared, it nevertheless can be interpreted similar to it (Borcard et al. 2018, 256 passim).

The fit of the regression is now treated as the coordinates of the point cloud and the algorithm returns to base CA. Metaphorically spoken it rotates the point cloud so that plotting a 2D shadow of that point cloud onto paper would show the most informative view. In technical terms: When we apply a new orthogonal coordinate system to the points after the rotation, the points are most spread out along the first (horizontal) axis i. e. the new axis is the length axis of the point cloud. The width of the point cloud is covered by the second (vertical) axis. Further axes cover further aspects of the point cloud's size but are rarely used in analysis. One important aspect refers to the scaling of the row point coordinates. The rotation moves the whole system, not only the row points but also the former type frequency axes which, in a way, represented the coordinate system before the rotation. Now one could simply use the row point coordinates which result from the rotation using the fitted values, they are called 'linear constraint(s)' or just 'lc' scores (coordinates) (Oksanen et al 2016; Borcard et al. 2018, 216). But we recommend to choose so called weighted average coordinates for the rows. That is, the row's points are placed at weighted averages of those type axis coordinates which are present in the rows and the weights are the type frequencies themselves. In CCA they are called 'weighted averages' or simply 'wa' scores. Strictly speaking, such a placement of the row points does neglect some parts of the linear combinations established before, but uses instead the shape of the rotated type space and its relation to the constraint. In other words, 'weighted average' coordinates in CCA also include sampling noise. And since archaeological data can always be considered to be noisy we like to keep that aspect.

Having submitted the fits of a regression to the CA rotation the new space clearly can only consist of as many dimensions as the constraining variables can define. In case of metric variables each constraint adds one canonical dimension (cf. Legendre & Legendre 2012, 637). In our case it will be only one constraint and therefore only one so called canonical axis. So in our case this step amounts less to a rotation than to a direct projection of the multi-D space onto a 1-D space i.e. a line. The remaining unconstrained information of the table represented by the residuals of the regression, can be submitted to a CA to afterwards combine constrained and unconstrained results (cf. Legendre & Legendre 2012, 666). This has become the standard in CCA due to the implementation of the algorithm by Jari Oksanen (Oksanen et al. 2016).

At the end the analysis should also include a permutation test of the relation between constraint(s) and counts. This test is very simple and intuitive: just permute the values in the constraining column(s) among the rows, repeat the whole computation and count how many outcomes result in a similar high value for explained inertia. If less than 5 percent of the outcomes exibit a similar high amount of explained inertia, consider the causal relation as 'most probably not random'. Note, this test is one of the great advantages of a canonical ordination method over intuition. It clearly identifies nonrandom causal relations in a reproducible way.

Now we already have a three-part result. First there is the test telling us if we can assume a nonrandom causal relation between the constraining variable(s) and the compositions represented by the count data table. Second we have a measure of how strong that relation is (amount of explained inertia). And finally we can illustrate the relation in a 2D plot called a triplot. In a triplot our cases (rows) are mapped as points where similar cases are close together. The types (columns) are also represented by points where projecting a row point onto the connection between the type point and the origin of the axes allows to reconstruct the percentage of the respective type in the count composition of that row point (for a comprehensive interpretation of biplots and triplots see Borcard et al. 2018, 175 and 258). Note, all the information we see along canonical axes is that related to the constraint(s). Important aspects may be missing along CCA1 – but in a canonical approach this may be of less concern. However, all information not covered by the constraint is still preserved on the CA axes, so it is not lost – just side-lined for the moment.

And while, as mentioned, the application of unconstrained ordinations to analyse the compositions of hunter/gatherer assemblages is an established approach (Mahlstedt 2015; Spies 2016; Küssner 2009), applying canonical ordinations to connect composition and causal forces is a rather recent development. A successful example is the study of Levantine Upper Paleolithic assemblage compositions in their relation to landscape types (Parow-Souchon 2020). But canonical ordination offers additional possibilities which to the best of our knowledge have not been used in archaeology before. The innovation we present here is just the transfer of an aspect of CCA which is used for decades in e.g. Paleo-Ecology. It is not our invention nor did we develop any computations or software. We just applied what is already there – only for the first time in an archaeological setting.

Consider that a canonical ordination establishes the relation between the count data and the constraining variable(s) by a formula (linear combination) with a left hand side (LHS) and a right hand side (RHS). Such a formula can be solved not only for the LHS (i.e. count data information related to constraint) but also for the RHS (i.e. value of constraint related to counts) i.e. which counts stand for which value of the constraining variable(s). Obviously for given data this makes no sense since the values of the constraining variable(s) must be known to establish the formula. Now what if we can describe new assemblages by the same typology but do not have values for the constraining variable(s)?

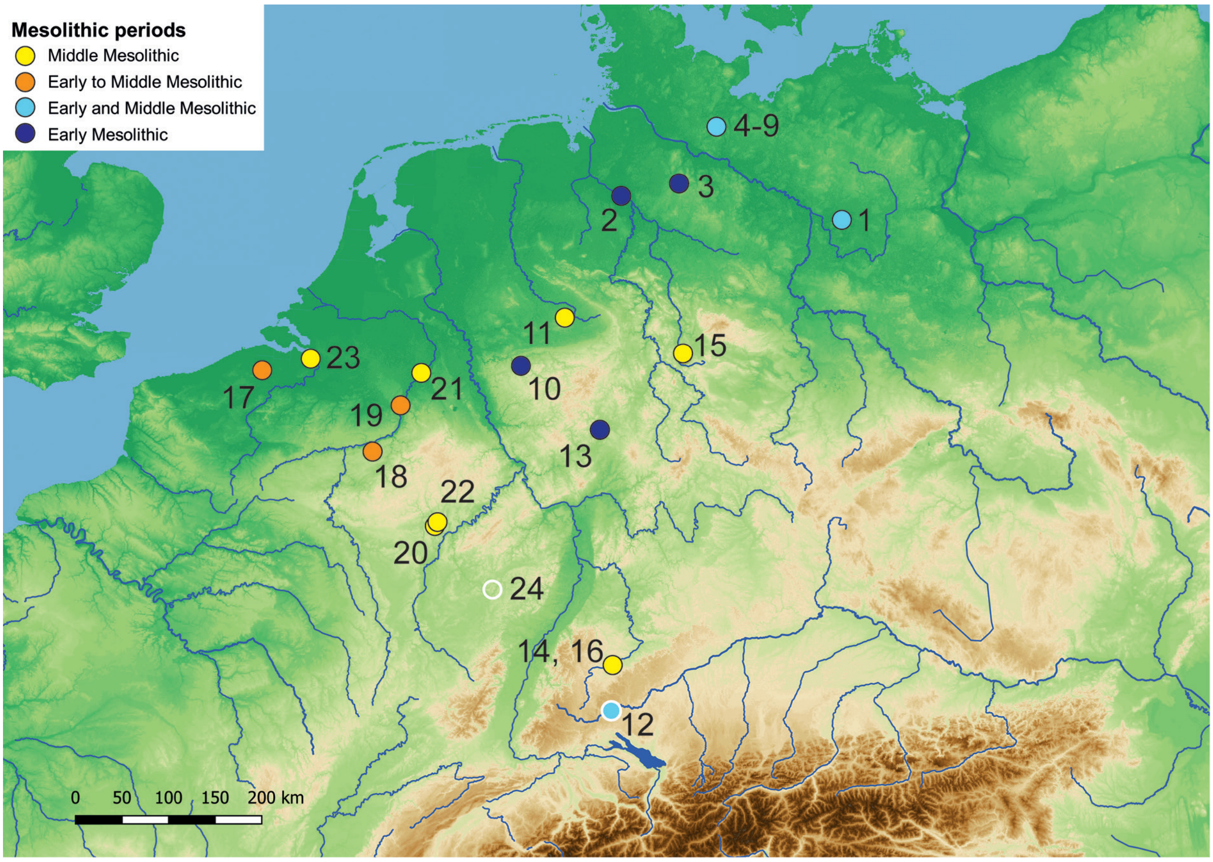

Fig. 2 Geographical setting of the 23 sites with C^{14}-dated microlith-complexes used for the CCA. The sites marked with a white circle are Reinheim 'Allmend C' (site 24) and layer 11 of the Jägerhaus-Höhle (site 12). In brackets number of dated microlith-complexes used per site: **1** Friesack 4 (10); **2** Achim-Bierden (1); **3** Haverbeck (1); **4-9** Duvensee (6); **10** Rieger Busch (1); **11** Oelde-Weitkamp 2 (1); **12** Jägerhaus-Höhle (2); **13** Niederweimar 6 (1); **14** Rottenburg-Siebenlinden 1 (1); **15** Abri Bettenroder Berg IX (2); **16** Rottenburg-Siebenlinden 3-5 (1); **17** Oostwinkel-Mostmolen (1); **18** Trou Al'Wesse (2); **19** Neerharen - de Kip (1); **20** Abri Kalekapp 2 (1); **21** Haelen-Broekweg (1); **22** Abri "Auf den Leien" (1); **23** Doel-Deurganckdok (1) (map B. Gehlen).

Fig. 2 Geographische Lage der 23 Fundstellen mit ^{14}C-datierten Mikrolith-Komplexen, die für die CCA verwendet wurden. Die Fundstellen mit dem weißen Kreis sind Reinheim ‚Allmend C' (Fundplatz 24) und die Schicht 11 der Jägerhaus-Höhle (Fundplatz 12). In Klammern steht die Anzahl der datierten Mikrolith-Inventare pro Fundstelle: **1** Friesack 4 (10); **2** Achim-Bierden (1); **3** Haverbeck (1); **4-9** Duvensee (6); **10** Rieger Busch (1); **11** Oelde-Weitkamp 2 (1); **12** Jägerhaus-Höhle (2); **13** Niederweimar 6 (1); **14** Rottenburg-Siebenlinden 1 (1); **15** Abri Bettenroder Berg IX (2); **16** Rottenburg-Siebenlinden 3-5 (1); **17** Oostwinkel-Mostmolen (1); **18** Trou Al'Wesse (2); **19** Neerharen - de Kip (1); **20** Abri Kalekapp 2 (1); **21** Haelen-Broekweg (1); **22** Abri "Auf den Leien" (1); **23** Doel-Deurganckdok (1)

In such a setting it makes perfect sense to take the established formula and solve it for the RHS i.e. use the relation established by the old assemblages to statistically estimate the value of the constraint(s) for the new assemblages. Such an approach is known as calibration of a CCA model (Oksanen et al. 2016). It is a long standing practice e.g. to reconstruct paleo-climate or environment data from species composition in lake sediments for paleo-lakes (Legendre & Birks 2012). Beware, the calibration of a CCA model must not be confused with the calibration of a radiocarbon date. Calibration within the CCA setting refers to the inverse solution of the relation formula and not to the adaption of a radiocarbon date to the calendar scale by correcting for changes in the atmospheric production of that isotope.

Microliths for Dating

The following CCA uses microlithic inventories, which date between about 9000 and 7800 cal BC

site / layer / layer complex	abbrev.	C225	C221	C034	C036	C23j	C228	C125	D023	D013	C21k	C031	C027	F023	C27j	C011	E040	C033	C024	D029	D028	D031	D022	D110	C22g	D021
Doel "Deurganckdok"	DD	1	0	0	0	0	0	0	1	0	1	3	0	0	0	0	3	0	2	0	0	0	0	0	0	4
Rottenburg-Siebenlinden 1, AH II	RS12	0	1	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	1	0	0	0	1	1	0	2
Duvensee WP 13	Du13	0	0	1	2	1	0	0	3	0	0	5	0	0	0	0	0	0	1	0	1	0	8	0	1	14
Friesack 4 III c	F43c	0	0	0	0	0	0	0	12	0	0	6	1	0	0	0	4	0	0	0	2	1	12	0	0	26
Hersberg	Heb	0	1	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	1
Rottenburg-Siebenlinden 3-5, AH IV	RS34	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	2	0	2
Bettenroder Berg IX, layer 10	BB10	1	1	0	0	0	1	0	6	0	1	0	4	1	1	4	3	0	1	0	0	0	4	0	1	8
Jägerhaus-Höhle, layer 10	Jä10	0	0	0	0	0	0	3	0	0	0	0	2	0	0	0	0	0	0	0	1	0	0	0	0	1
Oelde-Weitkamp 2	OW2	1	1	0	0	2	0	0	0	0	0	2	2	0	0	0	4	1	0	0	0	0	1	4	0	8
Jägerhaus-Höhle, layer 11, pollen analysis	Jä11	0	0	0	0	0	1	3	0	2	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0
Friesack 4 III b	F43b	0	0	1	2	0	0	0	6	0	0	11	5	0	0	4	11	2	3	7	29	0	42	0	0	95
Duvensee WP 6	Du6	0	0	0	0	0	0	0	0	0	0	0	3	1	0	0	0	0	0	2	7	0	6	2	0	46
Bettenroder Berg IX, layer 13	BB13	0	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	4
Friesack 4 III a	F43a	0	0	0	0	0	0	0	0	0	0	3	1	0	0	0	2	0	0	0	0	1	7	0	0	8
Haelen Brokweg	HaB	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	5
Abri Kalekapp, layer 2	Ka22	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	1	0
Friesack 4 II d	F42d	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	3	1	0	11
Duvensee WP 1	Du1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1	1
Trou Al'Wesse, layer b beta	W4bb	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Trou Al'Wesse, layer b gamma	W4bg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
Nerhaaren de Kip	NeKi	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Duvensee WP 2	Du2	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	5	0	0	9
Reinheim 'Allmend C', soil science	Reih	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	1	0	1
Oostwinkel "Mostmolen"	OstM	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	3	0	1	0	0	0	0	0	0	0
Rieger Busch	RiB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
Friesack 4 II c	F42c	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Friesack 4 II b	F42b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	2	0	0	3
Haverbeck	Habe	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Duvensee WP 8	Du8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Duvensee WP 9	Du9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jägerhaus-Höhle, layer 13	Jä13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Niederweimar 6	Niw6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Achim-Bierden 30	Abi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Friesack 4 I c	F41c	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	3
Friesack 4 I b	F41b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Friesack 4 Ia	F41a	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	sum types	3	5	2	4	3	2	7	30	5	3	35	29	2	2	10	31	3	12	10	42	2	100	12	5	257

regions

northern Germany; Friesack 4 (Brandenburg); middle range mountain in western Germany; western Germany; BeNeLux-countries; south western Germany

C023	C025	C026	F025	C210	C042	C028	B	E020	C227	D012	C27k	D011	C037	C021	C22j	C127	A	C010	F031	C128	C038	D014	D027	C120	C022	C029	sum microliths	calBC average values	chronozone	Mesolithic period
2	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	7677	middle Boreal	medium Middle Mesolithic
0	1	0	0	1	0	0	4	1	1	2	1	2	0	0	0	0	0	2	0	0	0	0	0	1	3	0	28	7765		
2	0	0	2	0	1	0	0	0	0	0	0	4	0	3	0	0	0	2	0	0	0	0	0	0	1	0	52	7769		
4	2	0	2	0	0	0	0	2	0	0	0	7	4	11	0	0	3	4	0	0	0	0	2	0	9	0	114	7873		
0	0	0	0	0	0	0	2	0	0	0	1	1	0	0	0	2	0	1	0	0	0	0	0	0	0	0	14	7883		
0	0	1	0	0	0	0	0	0	0	2	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	13	7886		
4	0	0	3	0	0	1	5	3	1	2	1	3	0	7	1	1	3	17	0	1	0	0	0	2	5	0	97	7927		
0	1	1	0	0	0	0	0	0	0	0	0	2	0	2	0	1	0	0	0	0	0	0	0	0	6	0	20	7961		
0	4	0	1	0	1	0	0	2	0	0	0	0	3	6	0	0	1	1	0	0	0	0	0	0	2	1	48	7987		
3	3	1	0	0	0	0	0	0	0	3	0	0	0	1	0	4	2	3	0	0	0	0	0	0	1	0	31	0	early Boreal	ancient Middle Mesolithic
9	15	3	10	0	3	1	4	9	0	0	0	39	3	29	0	0	17	18	1	0	1	1	0	0	35	1	417	8121		
1	7	1	2	0	0	0	1	2	0	3	0	13	0	6	0	0	3	13	4	0	0	0	0	0	8	0	132	8138		
0	0	0	1	0	0	1	2	2	0	1	0	1	0	2	0	0	4	2	0	0	0	0	0	0	1	0	25	8139		
1	2	0	1	0	0	1	0	2	0	0	0	4	1	2	0	0	0	0	0	0	0	0	1	0	5	1	43	8248		
0	1	0	1	0	0	0	2	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	3	0	17	8264		
1	0	0	0	0	0	1	4	2	0	0	1	1	0	3	0	1	0	2	0	0	0	0	0	0	12	0	32	8424		
0	0	1	1	0	0	0	1	0	0	0	0	0	2	0	0	0	3	7	0	0	0	1	0	0	2	1	36	8426		
1	0	0	0	0	0	1	1	0	0	0	0	4	0	3	2	0	3	14	0	0	0	0	0	0	8	0	41	8429		
0	0	0	0	0	0	0	1	0	0	5	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	9	8456		
0	0	0	0	0	0	0	1	0	0	3	2	0	0	3	0	0	0	0	0	0	0	0	0	0	2	0	13	8402		
0	0	0	0	0	0	0	6	0	0	0	0	3	1	4	0	0	0	0	0	0	0	0	0	0	11	0	29	8464		
5	0	0	1	0	3	1	0	0	0	1	0	3	0	3	0	0	0	7	2	0	0	0	0	0	0	3	45	8552	late Preboreal	late Early Mesolithic
1	0	0	0	0	0	0	0	3	1	0	1	3	0	4	0	1	0	0	0	0	0	0	0	0	7	0	25	0		
0	1	0	0	1	0	0	4	0	2	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	8	0	26	8572		
1	0	0	0	0	0	1	2	0	0	0	1	1	4	5	0	2	1	0	0	0	0	0	0	0	7	0	27	8589		
1	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2	0	0	0	0	0	0	0	0	5	8645		
1	2	0	0	0	0	0	0	1	0	0	0	2	3	0	0	0	0	2	0	0	1	0	0	0	7	1	26	8790		
0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	10	0	12	8757		
0	0	0	0	0	0	0	0	2	0	0	0	0	0	11	0	0	0	10	0	0	0	0	0	0	40	0	63	8879	middle Preboreal	ancient Early Mesolithic
0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	5	3	0	0	0	0	0	0	26	0	39	8879		
0	0	0	4	0	0	0	0	0	0	4	1	19	0	1	0	4	7	7	0	1	0	0	0	4	1	0	54	8984		
0	1	0	2	0	0	0	1	1	0	0	0	1	0	8	0	1	2	9	0	0	0	1	0	0	6	0	34	8995		
1	0	0	0	0	0	0	3	0	0	0	1	0	0	1	0	0	0	5	0	0	0	0	0	0	2	0	13	9013		
0	0	0	0	0	0	0	0	1	0	0	0	1	0	2	0	0	0	1	0	0	0	0	1	0	3	2	16	9031		
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	4	9022		
0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2	4	1	0	0	0	0	0	9	0	18	9048		
38	40	8	32	2	8	8	45	35	5	26	12	114	21	132	3	18	57	136	8	2	2	3	5	7	241	10	1636			

types

end-retouched microliths; backed bladlets; micro-points; lancet points; triangles; segments; squares

Fig. 3 Data with sites/find layers (rows) and microlith types (columns) of 14C-dated complexes used for canonical correspondence analysis. More than 1600 microlithes were examined as original artefacts or were recorded from publications with drawings.
The microlith forms were assigned certain colours according to their membership of type groups:
Orange for end retouched microlithes; **purple** for backed bladlets; **light blue** for micro points; **medium blue** for lancet points; **green** for triangles; **pink** for segments; **yellow** for squares on irregular blades.
The data were compiled by Nele Schneid and Birgit Gehlen (graph B. Gehlen).

Abb. 3 Daten mit Fundplätzen/Fundschichten (Zeilen) und Mikrolith-Typen (Spalten) von 14C-datierten Komplexen, die für die Kanonische Korrespondenzanalyse verwendet wurden. Mehr als 1600 Mikrolithen wurden als Originalartefakte bzw. aus Publikationen mit Zeichnungen untersucht.
Den Mikrolithformen wurden je nach Zugehörigkeit zu Typengruppen bestimmte Farben zugewiesen:
Orange für endretuschierte Mikrolithen, **Lila** für Rückenmesser; **Hellblau** für Mikrospitzen; **Mittelblau** für Lanzettspitzen; **Grün** für Dreiecke; **Rosa** für Segmente und **Gelb** für Vierecke aus unregelmäßigen Klingen.
Die Daten wurden von Nele Schneid und Birgit Gehlen zusammengestellt (Graphik B. Gehlen).

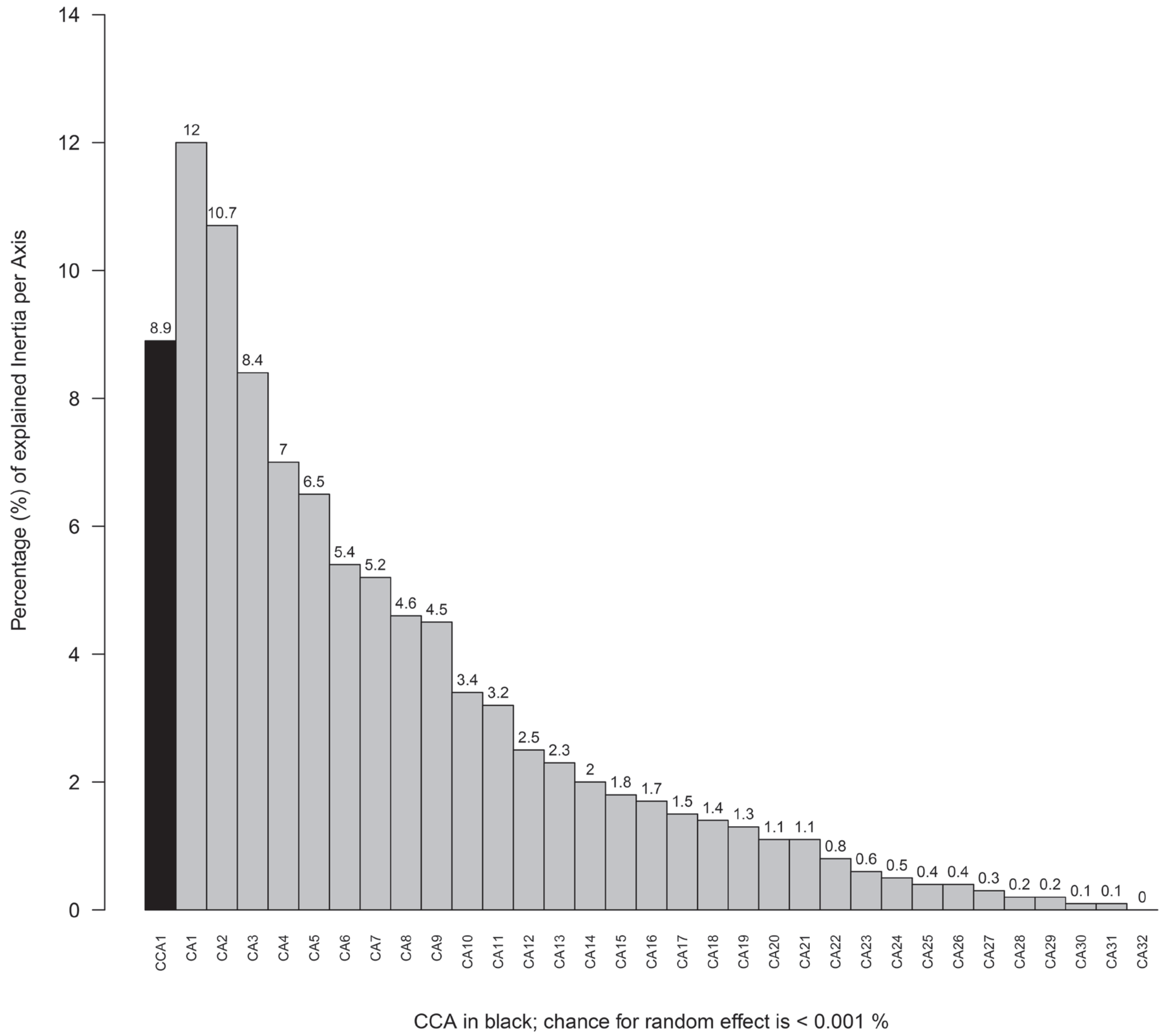

Fig. 4 Screeplot for the CCA of microlith assemblage composition constrained by chronology. Explained inertia amounts to 8.9 % of total inertia, that is, 8.9 % of information embedded in the assemblage compositions. Significance of the CCA model is estimated by a permutation test with 99999 permutations resulting in a permutation p-value of 0.00001 (for producing this figure with R code see **appendix D paragraph 3.1**).

Abb. 4 Kanonische Korrespondenzanalyse der Mikrolithinventare bedingt nach Datierung: Eigenwertdiagramm. Die Säulenhöhe bezeichnet den Anteil am unterschiedlichen Typ-Auftreten, den die jeweilige Achse erfasst. Die kanonische Achse „CCA1“ erklärt 8,9 % (‚explained inertia‘) der Häufigkeitsunterschiede; sie ist hochsignifikant (99999 Permutationen; Permutations-p-Wert 0,00001) (der R-Kode für die Erzeugung dieser Abbildung steht in **Appendix D Abschnitt 3.1**).

from Germany and the BeNeLux-countries (**Fig. 2**). Thus they belong to the middle and late Preboreal and early and middle Boreal phases (see **Fig. 3**). The selection of the dated inventories was determined on the one hand by the time span and on the other by the quality of the data. Not all complexes were used for comparison, which provided C^{14}-data. For some of them the dating seemed too old or too young, as in the inventories of Sarching '89/'90 (Heinen 2005), Ourlaine in Belgium (Lausberg & Pirnay 1980; 1981) or Altwies-Haed in Luxembourg (Ziesaire 1983). For others exact details or drawings of the microlithes are missing, as in the case of Verrebroek-Dok in Belgium (Crombé 1998). In **Appendix A** only those types have been compiled which were also used for the CCA. A publication of the complete typology prepared by Gehlen et al., of which an early version is published by Thomas Richter (2011), is planned for the nearer

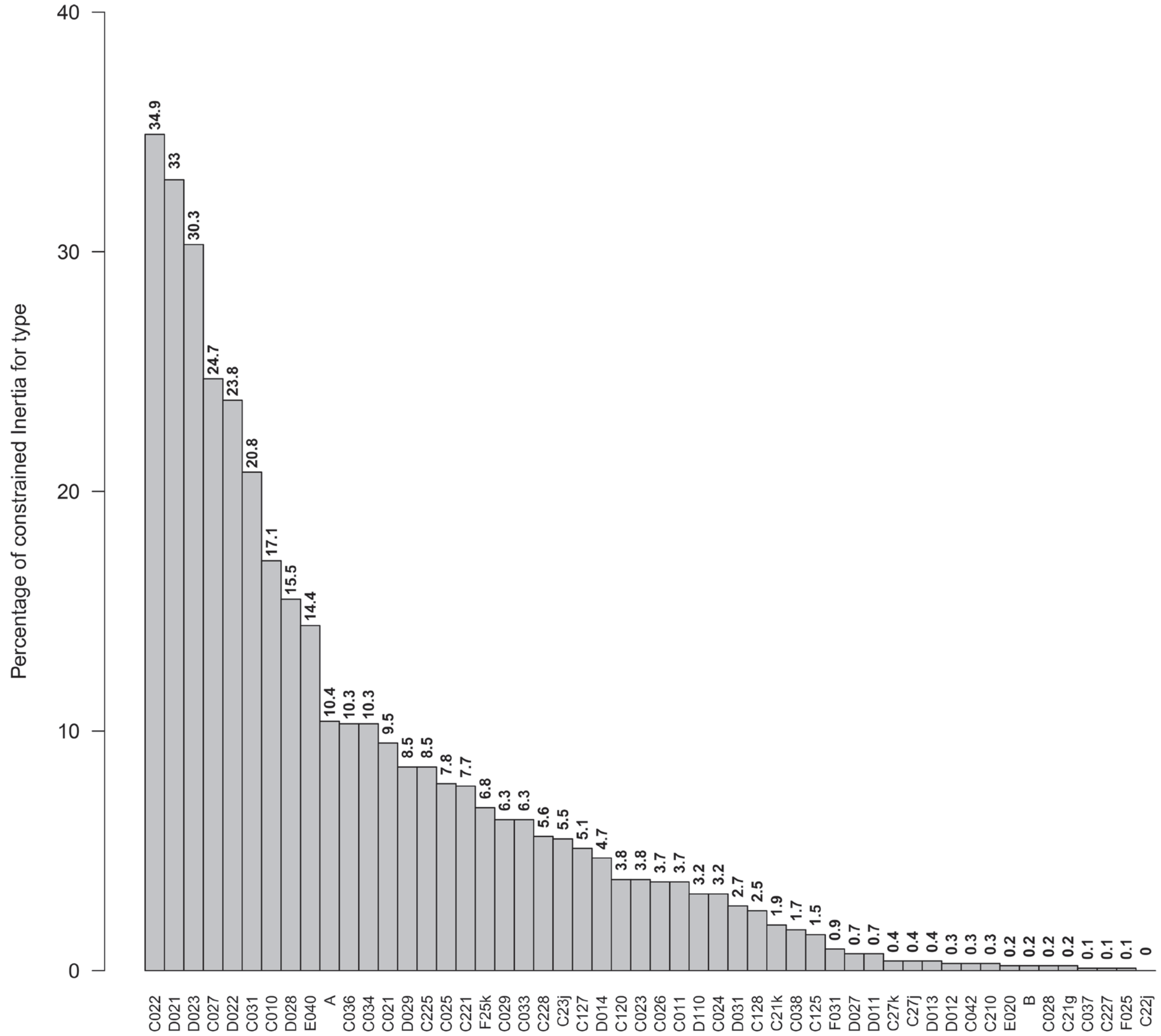

Fig. 5 Amount of explained inertia for each type (see text) by the CCA of microlith assemblage composition constrained by chronology. Especially the types C022 down to E040 exhibit a rather strong relation to chronology i.e. differences in their frequencies are strongly related to chronology. Note the elbow between type E040 and type A (for producing this figure with R code see **appendix D paragraph 3.2**).

Abb. 5 Kanonische Korrespondenzanalyse der Mikrolithinventare bedingt nach Datierung: kanonisch erklärbare Inertien. Der kanonische Anteil ist der Anteil der Häufigkeitsunterschiede der Mikrolithen, der mit der Kovariablen „Datierung" erklärbar ist. Vor allem die Häufigkeitsunterschiede bei den Typen C022 bis E040 sind zeitlich bedingt. Man beachte den sog. Ellbogen zwischen Typ E040 und Typ A (der R-Kode für die Erzeugung dieser Abbildung steht in **Appendix D Abschnitt 3.2**)

future. However, the publication of the typochronology of the Late Mesolithic in Western Central Europe between ca. 6800 and 5300 cal BC is already in preparation.

Two microlith types without numbers – A and B – stand for two and three different forms of end retouched microliths and backed bladlets respectively. However, they have been combined, as they are only rarely found.

As an example for the dating of non-radiocarbon-dated inventories with the help of the CCA, two find complexes were selected from which well-documented microlithic ensembles are known. These are Reinheim 'Allmend C', an open-air site from Saarland (Donié et al. 1999), and layer 11 of the Jägerhaus-Höhle on the upper Danube in Baden-Württemberg (Taute 1971; 1975).

Here we apply a CCA to our microlith data table and use C^{14} age – that is chronology – as the constraint. 36 assemblages from the Preboreal and the older Boreal are described by our microlith typology of 52 types resulting in a table with 36 rows and 52 columns of count data. As constraint we used calibrated radiocarbon ages, stored in the last column of the data table. The radiocarbon dates presented in this paper were calibrated by one of us (Zander) using OxCal v4.4.2 (Bronk Ramsey 2009) which works with IntCal20 (Reimer et al. 2020). With the recent advances of IntCal20 (Reimer et al. 2020), the calibration curve now extends to 55,000 cal BP with a fully atmospheric record based on tree rings to 13,900 cal BP. For replicate measurements, weighted means were calibrated using the R_Combine command in OxCal (cf. Ward & Wilson 1978). The mean of the the maximum probability was taken as age, calling our constraint 'cal BC'.

So the total data set (see **appendix C**) is a table of 36 rows and 53 columns, the last column holding the constraint. But only 34 of our assemblages yielded radiocarbon dates, two, Jägerhaus-Höhle layer 11 and Reinheim 'Allmend C', can be dated only provisionally by an educated guess – and are estimated to be of late Preboreal age in the case of Reinheim and of middle Boreal in the case Jägerhaus-Höhle layer 11.

We used the free and open source statistical programming software R (R Core Team 2019) for all our computations. For CCA we applied the *R* extension package *vegan*, programmed by a group of the world leading multivariate ecologists under the supervision of Jari Oksanen (Oksanen et al. 2016). The CCA model itself was computed by function *cca()* from that package. That is, we implemented standard procedures with standard R code.

To allow interested readers educated in R for in detail reproduction of our results we added the R code as **appendix D**. In this code every step beginning with the data import and preparation, followed by the computation of the CCA, the test and the production of the illustrations is presented in numbered paragraphs and annotated with explanatory comments. The central steps are **appendix D paragraph 2.1**, the computation and test of the CCA, and **appendix D paragraph 2.2.2**, the calibration step i. e. the estimate of the cal BC dates for the two undated assemblages. How to implement a CCA with vegan in R is explained – for fish species in and environment data of French river Doubs – in the volume 'Numerical Ecology with R' (Borcard et al. 2018) in the chapter on CCA. Please consider our R code to be just an archaeological example implementation.

Every multivariate analysis involving an ordination, be it a simple or a canonical ordination, should start by presenting how the information of the data table is covered by the ordination axes (**Fig. 4**). In PCA as well as in CCA this diagram is known as a scree plot, while in PCA (and RDA) the information, or say spread, is measured by (co-)variance, in CA and CCA it is measured by inertia, which – overly simplified – can be considered a sort of weighted (co-)variance. Since the actual numbers for the inertia value of each axis depend on the count values i. e. their values are different for each table, a screeplot usually presents constrained (explained) and unconstrained inertia as percentage of total inertia with appropriately sized bars. The size of all bars sum to a value of 100.

At first look a canonical axis covering only 8.9 % of total inertia as inertia explained by the constraint 'calibrated radiocarbon age' may be disappointing. But if one considers all past cultural phenomena, all taphonomic processes, all problems of recovery and classification acting on the mircolith data one realizes that any causal force acting on such a multivariate phenomenon can at best cover only a minor part of all information in such a table. Second, we often tend to ignore all imprecisions inherent to radiocarbon dating, beginning with the connection between date and dated phenomenon and not ending with a calibrated date representing a probability distribution and not a scalar value as implied by the use of one value per assemblage. The effects of dating bulk samples (see above) may further contribute to degrade the structured signal in the relation between assemblage composition and date. So effects acting on both sides of the estimation formula can weaken the manifestation of the causal relation and decrease the amount of explained inertia. In fact, seemingly small percentages of explained inertia are rather common in ecology when only one constraint is applied (cf. Legendre & Legendre 2012, 661). Our 8.9 % of explained inertia are in fact a rather good result stating that despite all possible influences to the contrary, the CCA has detected a reasonably strong causal effect of chronology onto microlith assemblage composition and our constrained axis CCA1 displays a reasonable amount of multivariate information. But note, the next two unconstrained axes, CA1 and CA2 with 12 % and 10.7 % respectively, cover more inertia than the single constrained axis CCA1 of our model. There is still a lot of information in the data set, that cannot be connected to chronology.

Any presentation of explained inertia should also supply a p-value for the relation detected by the model to demonstrate that the relation detected by the model was not caused by random chance. Nowadays to compute a permutation test with a lot of permutations is not a problem anymore. We run 99 999 permutations which together with the empirical data set make for 100 000 manifestations and allow to decide about significance of the CCA model at the level of one thousandth part of one percent i. e. at a very reliable level. In fact, the significance of our CCA model is estimated to be much better than 0.1 % with a permutation p-value of 0.00001 indeed. The model's significance allows us to exclude that the relation between microlith assemblage composition and chronological age is caused by chance. The test was implemented by applying function *anova.cca()* from package *vegan* (Oksanen et al. 2016) to a R CCA model object produced by function *cca()* from the same package (see **appendix D paragraph 2.1**).

The concept of inertia can also be applied to measure for each type the amount of frequency differences between the assemblages i. e. the total inertia of a table can also be considered to be the sum all type inertiae (see Greenacre 2017, ch. 4). And of cause a CCA model allows to specify for each type the amount of its inertia which is explained by the constraint (**Fig. 5**). In other words, by looking at the percentage of type frequency differences which are related to chronology we can determine types whose abundances are strongly related to chronology and therefore make a sort of '*Leitfossil*' for certain periods. In our case the following microlith types represent – with decreasing strength – sensible chronological markers: C022 (*partially edge-retouched micro point* = 34.9 %), D021 (*Clearly unequal triangle* = 33 %), D023 (*Extremely unequal triangle* = 30.3 %), C027 (*Micro point with complete retouching of one edge and dorsal straight base retouch* = 24.7 %), D022 (*Strong unequal triangle* = 23.8 %), C031 (*Edge-retouched lancet point* = 20.8 %), C010 (*Micro point with oblique retouch* = 17.1 %), D028 (*Clearly unequal triangle with concave retouched short side* = 15.5 %) and E040 (*Elongated symmetrical segment* = 14.4 %).

Note, that setting a threshold for sensible markers at about 10 % of explained inertia is a rather arbitrary decision and should be seen as our personal evaluation of the numerical results. There is only one hint in the structure of the barplot: down to E040 explained inertia decreases rapidly while below, beginning with type A, explained inertia decreases only slightly between types. This structure is called an elbow in multivariate statistics and can be used as an empirical decision rule. Here this so called elbow criterion is our only argument for highlighting types C022 to E040 as sensible chronological markers.

Before we turn to the visualization of the CCA model via a so called triplot, we report the estimates produced by the function *calibrate()* from R package *vegan*. Both estimates for calibrated age, cal BC, of the two undated assemblages, Jägerhaus-Höhle layer 11 and Reinheim 'Allmend C', are rounded to the decade. Reinheim is thought to be of early Preboreal age according to typological considerations and the results of extensive pedological research at the site (Donié et al. 1999; Brück & Kobiniok 1998-99). The calibration step of the CCA asigns an estimated date of about 8560 cal BC at the end of the Preboreal, which is perhaps some hundred years younger as assumed by the cited authors (Early Mesolithic/Preboreal). This discrepancy is most probably caused by the singular occurence of the rare type C027 (micro-point with complete retouching of one edge and dorsal straight base retouch), which is frequent in many younger assemblages (see **Fig. 3**) and is identified as strongly related to chronology (see **Fig. 5**). Remember that all CA based approaches emphasize rare types more heavily – which is maybe a flaw in that special case.

The estimated cal BC age for Jägerhaus-Höhle layer 11 is about 8080 cal BC. Here we can check the result for consistency with the other dates available for layers from the Jägerhaus-Höhle. Layer 10 immediately above layer 11 has an age of 7960 cal BC, rounded to the decade. And layer 13 below layer 11, and separated by layer 12, has an age of 8980 cal BC, rounded to the decade. That is, the estimate for layer 11 is placed reasonably in between the existing dates. This estimate fits also well to the pollen record, which is published to be from the earlier Boreal period (Filzer 1978, 26 f.), and is a specification of the dating by the determination of the charcoal remains (Schweingruber 1978, 42 f.). It also tells us, that in favourable conditions our model is able

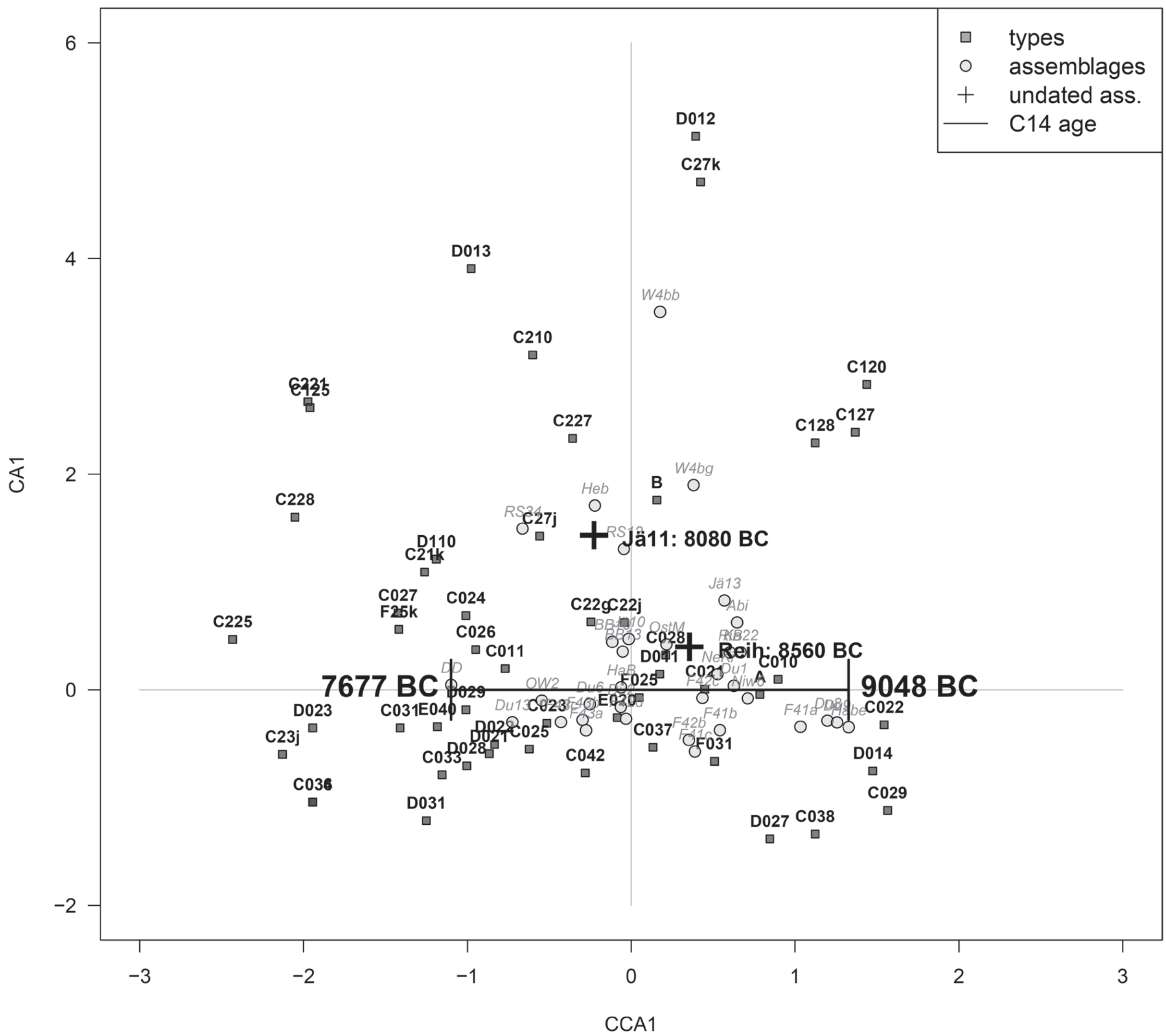

Fig. 6 Triplot for the CCA of microlith assemblage composition constrained by chronology. The triplot consists of the only constrained axis of the model, CCA1, and the first unconstrained axis CA1. The coordinates are in scaling 1 i.e. distances between assemblages approximate chisquare distances between the count data rows i.e. we display a row isometric map (see text). Types act as vertices of the multidimensional space. Assemblages projected onto the connection between a type point and the origin exhibit frequecies higher than average of that type. The horizontal axis represents time running from right to left with the oldest assemblages on the right. The two undated assemblages, Jägerhaushöhle layer 11 and Reinheim 'Allmende C', are displayed with their respective estimated date, rounded to the decade (for producing this figure with R code see **appendix D paragraph 3.3**).

Abb. 6 Kanonische Korrespondenzanalyse der Mikrolithinventare bedingt nach Datierung. Das Ordinationsdiagramm (Triplot) besteht aus der kanonischen Achse CCA1 und der ersten einfachen Korrespondenzanalyse-Achse CA1. Die Inventare und Typen sind in sog. Koordinatenskalierung 1 (=Zeilenprinzipal-Koordinaten) dargestellt, d.h. die Abstände zwischen den Inventarpunkten entsprechen näherungsweise ihren Chiquadratdistanzen.Typpunkte bilden die Eckpunkte des multidimensionalen Raumes. Projiziert man einen Inventarpunkt auf die Linie Achsenursprung-Typenpunkt, erkennt man, wie überdurchschnittlich hoch der Typanteil beim Inventar ist. Die horizontale (kanonische) Achse repräsentiert die Datierung von rechts (alt) nach links (jung). Die zuvor undatierten Inventare Jägerhaushöhle Schicht 11 und Reinheim 'Allmende C', sind mit ihrem gerundeten Schätzdatum dargestellt (der R-Kode für die Erzeugung dieser Abbildung steht in **Appendix D Abschnitt 3.3**).

to detect typo-chronological differences of about one century. In other words, the relation between the microlith assemblage compositions in our table and the assigned calibrated ages we used as constraining variable is so detailed as to allow us to detect differences of only 100 calendar years. And it holds another very important insight: the typology, which was developed by a workgroup comprising three of the authors (Gehlen/Schneid/Zander), is an extremely sensible multivariate measurement tool. So the CCA result encourages us to use this data and the typology it is based on for further canonical investigations. If possible we shall investigate space by using site coordinates. To decide which assemblages to include in such an analysis can already be identified as one for future work.

The classic illustration of any ordination, simple or canonical is a kind of map showing several aspects of the data (see Borcard et al. 2018, 175 and 258). In CCA this is called a triplot (**Fig. 6**), because it depicts three kinds of information: the ordering of the rows (assemblages as points), the structure of the multivariate space as defined by the types (types as squares) and the relation of the 2D projection of the multivariate space to the constraining variable. Constraining variable(s) are usually represented by arrow(s). But our canonical space is only one dimensional, since we only applied one constraint only. The second and all other dimensions are unconstrained CA axes. For better readability we omit the arrow and plot the time scale as a bar along the first canonical, horizontal axis CCA1 with older ages to the right. An arrow would also be parallel to CCA1. Since the extreme values of the constraint 'cal BC' are known, we can annotate the bar.

Note, this representation of a constraining metric variable as a bar with annotated values is a special case indebted to having only one constraint. With several metric constraints they should always be displayed as arrows.

The row points of our data table, the assemblages, are plotted in so called principal coordinates (Greenacre 2017, ch. 8); in ecology this kind of coordinates is called scaling 1 (Legendre & Legendre 2012, 434); in econometrics it is called row-isometric display (Beh & Lombardo 2014, 134). Technically one can say the row points are placed at doubly weighted eigenvectors of the data table, one set of weights being the square root of its inverse row sums and the other the square root of the eigenvalues. Whenever an ordination of the row points is sought, one should apply scaling 1. For points mapped in that way the distances in the triplot approximate chisquare distances between assemblages. These distances have a clear interpretation: the closer two points are to each other, the more similar are their compositions when rare types are emphasized.

Types display the shape of the multidimensional space. They are the 2D 'shadows' of the extreme corners of the multivariate space, sometimes called vertices. This kind of coordinates is known as standard coordinates (Greenacre 2017, ch. 8). Project a row point onto the connection between a type point (in standard coordinates resp. scaling 1) and the origin and one can reconstruct the frequency of that type in the respective assemblage. An assemblage (row point) whose projection results in a position on the connecting line close to the type point consists nearly completely of specimen exhibiting that type. In the same manner one may project a row point onto the canonical axis to reconstruct its value of the constraining variable. In fact function *calibrate()* from package *vegan* is just implementing this projection numerically and outputs the reconstructed value of the constraining variable.

Type points which lay in roughly the same direction when looking from the origin represent types that are frequently occurring together in assemblages. Type points who are positioned far out in the direction of the constraint, or opposite to it, that is along the x axis, exhibit a close relation to the constraint. Here the triplot further elucidates the relation between chronology and types presented in **Fig. 5**. The micro-points C010 and C022 lay far out to the right which means their frequencies increase with the age of an assemblage, while e.g. the frequencies of types C031, D021, D022, D023, D028 and E040 decrease with the age of an assemblage, their points being situated far out to the left.

The ordering of the assemblages from right to left roughly represent their age as measured by cal BC dates. This may not be an exact reconstruction as the row point coordinates are of the 'weighted average' version and not of the 'linear constraint' version. Assemblages spread out along the vertical axis, CA1, are strongly influenced by causal forces not related to chronology. And the type points laying far out in the vertical are frequent in those assemblages. E.g. the two assemblages from Trou Al'Wesse (W4bg and W4bb) are both marked by relatively high

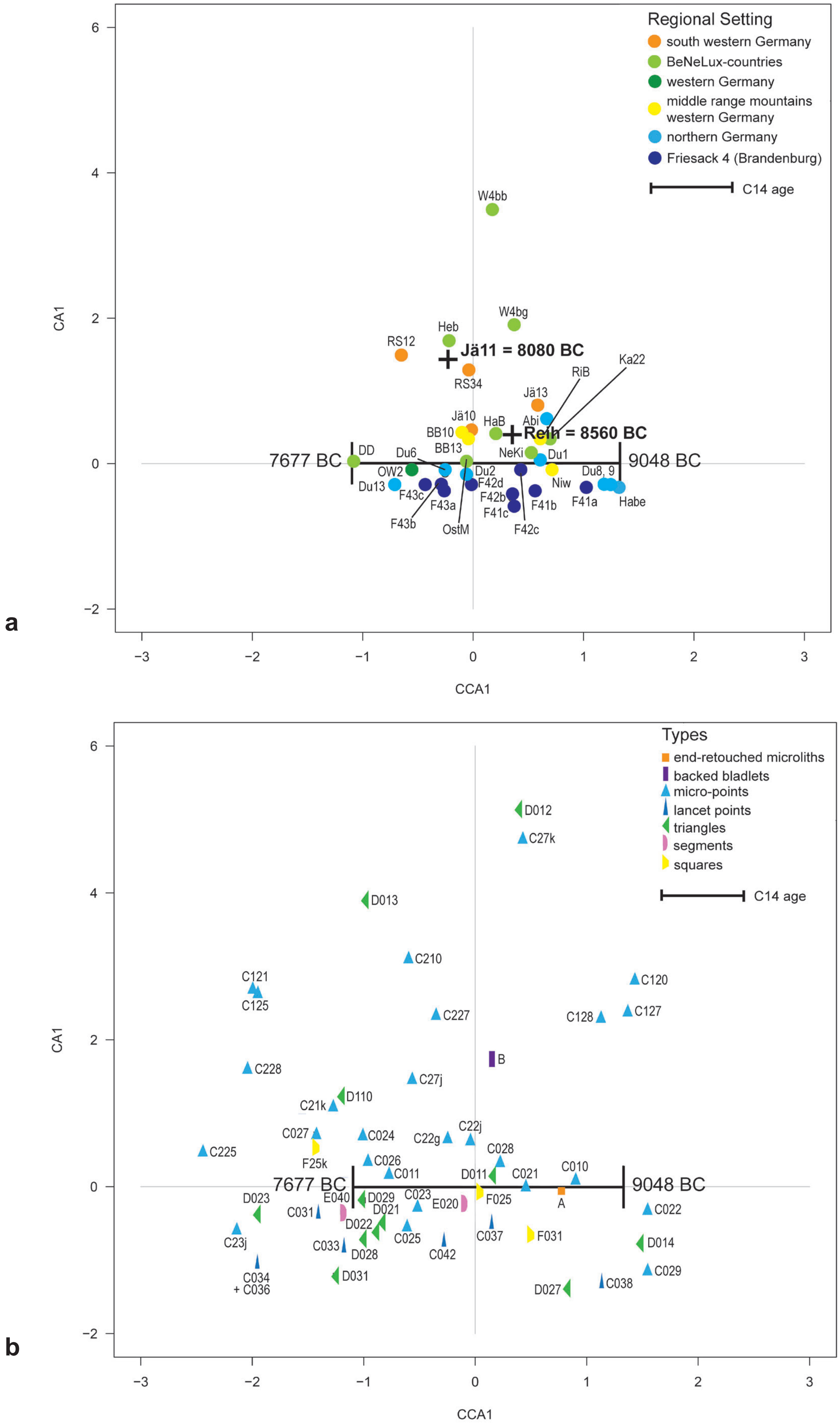
a
Regional Setting
south western Germany
BeNeLux-countries
western Germany
middle range mountains western Germany
northern Germany
Friesack 4 (Brandenburg)
C14 age
Jä11 = 8080 BC
Reih = 8560 BC
7677 BC
9048 BC
W4bb
W4bg
Heb
RS12
RS34
Ka22
RiB
Jä13
Jä10
HaB
Abi
BB10
BB13
DD
Du6
NeKi
Du1
OW2
Du2
Du13
F42d
Niw
Du8, 9
F43c
F42b
F41b
F41a
Habe
F43a
F41c
F43b
OstM
F42c
CA1
CCA1
b
Types
end-retouched microliths
backed bladlets
micro-points
lancet points
triangles
segments
squares
C14 age
7677 BC
9048 BC
D012
C27k
D013
C210
C121
C125
C120
C227
C128
C127
B
C228
C27j
D110
C21k
C22j
C027
C024
C22g
C028
C225
F25k
C026
C010
C011
D011
C021
D023
E040
D029
C023
E020
F025
A
C031
D021
C022
D022
C23j
C025
C037
F031
C033
D028
C042
D014
C034 + C036
D031
C029
C038
D027
CA1
CCA1

Fig. 7a (**p. 332**) The scatterplot of the sites and layers shows that some of the inertia covered by the first unconstrained axis CA1 are not related to chronology but seem to be related to a spatial aspect (coloured extract from triplot in **Fig. 6**; graph B. Gehlen).

Abb. 7a (**S. 332**) Die Streudiagramme der Fundstellen und -schichten zeigen, dass einige Inertia, die von der ersten freien Achse CA1 abgedeckt werden, nicht mit der Chronologie zusammenhängen, sondern mit einem räumlichen Aspekt (farbiger Auszug aus dem Triplot in **Abb. 6**; Grafik B. Gehlen).

Fig. 7b (**p. 332**) Scatterplot of the mircolith-types to recognize details of types and type-groups in their relations to chronology (coloured extract from triplot in **Fig. 6**; graph B. Gehlen).

Abb. 7b (**S. 332**) Streudiagramm der Mikrolith-Typen zur Erkennung von Details bei den Typen und Typengruppen in ihrem Bezug zur Chronologie (farbiger Auszug aus dem Triplot in **Abb. 6**; Grafik B. Gehlen).

frequencies of type D012 which has nearly no inertia explained by the model (see D012 with 0.3 % explained inertia in **Fig. 5**).

While a classical triplot is presented to evaluate all the relations between different pairs of informative elements (sites, types and contraint(s)) as an overview, scatterplots of single elements together with the constraint(s) e.g. only sites are also a valid way to display relations (sites **Fig. 7a** and types **7b**) among these points or between them and the constraint(s). An additional colouring by region (cf. **Fig 2**) facilitates comprehending additional aspects of the data. For instance, some of the inertia covered by the first unconstrained axis (CA1; **Fig. 7a**) i.e. inertia not related to chronology seems to be related to a spatial aspect. Some of the sites from southwestern Germany (RS12 = Rottenburg Siebelinden 1, AH II and RS34 = Rottenburg Siebelinden 3-5, AH IV) as well as some from the BeNeLux-region (Heb = Hersberg, W4bb = Trou Al'Wesse layer b beta and W4bg = Trou Al'Wesse layer b gamma) exhibit dissimilarities which may point that way. On the other hand, the majority of BeNeLux-region sites exhibit not much inertia related to CA1. Also the strata from the Jägerhaus-Höhle which are part of the model (layer 10 and layer 13) do not excel at CA1. So it remains a topic for further analysis to which extent regional traditions could explain the type spectra compositions.

A second phenomen deserves discussion here as well, because it touches on the way one can think about C^{14}-dates and also on the working principles of CCA, or say a statistical estimate. The site of Haverbeck (Habe) with a date of about 8760 BC (**cf. Fig 2**) is projected to the lower end of the constraint. Its age is estimated to be about 9040 BC when using its microlith spectrum which seems to be at odds with the data supplied. A similar effect but with an inverse result seems to be at work for the site of Achim-Bierden 30 (Abi) where a date of 9010 BC is estimated by the CCA as 8790 BC. The simple explanation for the coordinate position of Haverbeck is the importance (10 of 12 microliths) of micropoint type C022 in its assemblage. Since this micropoint type dominates at slightly older sites e.g. from the Duvensee area and we use the 'weighted average scores' (see above) its predominance moves Haverbeck towards these older sites. If we consider the nature of C^{14}-dates being probability distributions the estimated date is not completely outside the range for the possible real age of Haverbeck. Similar forces but now working in the opposite direction cause the CCA estimate to place Achim-Bierden 30 some 200 years younger than its most probable calibrated age. Here micropoints type C010 and C021 with 1 resp. 5 specimen making up nearly half of the only 13 microliths at Achim-Bierden 30 force the estimate to 'make it younger'. But again this is not completely unlikely when thinking about the possible age range for the real date of Achim-Bierden 30.

We note, only if we think of the most likely radiocarbon date as the true age, the CCA results for these sites seem a little bit odd. But if we take into account the nature of C^{14}-dates the contradiction vanishes. We have to add, however, that the result of a CCA is also no ground truth, it is just a reproducible estimate albeit highly significant. And while a significant statistical estimate is the best approach to capture a large scale trend – as is our CCA – it most probably cannot do justice to each and every single element of a sample.

In the same manner as considering spatial information deepened our understanding of the CCA results for the sites colouring of types by type-groups (**Fig. 7b**) is helpful to recognize details of their relations to chronology – or the lack of chronological relevance of a type. For instance, backed bladelets are present throughout the whole period covered here and cannot be expected to show a relation to the constraint. Consequently, they stand out on CA1 and are – so to say – at right angle with CCA1. Considering that vectors orthgonal to each other can be called independent, the position of type B is the geometric representation of that lack of chronological relevance.

Some type-groups exhibit a clear relation which can be transformed into a chronological description of armature type-history: while asymmetrical trapezes (F31) disappear towards the end of the period covered here, elongated symmetrical trapezes with one concave side (F25k) replace them and straight sided elongated symmetrical trapezes (F025) are present all the time. For segments (E020 and E040) the plot also elucidates some techno-history: while symmetrical pieces (E020) are present nearly all the time – with a peak in the last centuries of the 9th millenium causing the CCA to place them consequently at the center of CCA1 – their elongated versions (E040) takeover during the later phases. At this point one may have turned back to the data table (**Fig. 3**) and could have been tempted to say, well, I may draw the same conclusions by looking at the individual columns of that table – to which we would reply, yes, but one has also to admit, that the triplot or the scatterplots give a more neatly and comprehensive visual summary. And not to forget, any reproduction of the analysis by different researchers will lead to the very same result, which is not granted when different researchers look at **Fig. 3** and only state their impressions.

Conclusions

Our application of CCA consisted of an ordination of 34 microlith assemblages constrained by their C^{14}-age. The model indicated a potential relationship between assemblage composition as measured by our typology and age of the assemblage. In a further step we implemented a calibration of our CCA model to estimate the age of new, undated assemblages. This is an important extension for the tool set of statistical methods for chronological questions and the first time that such an instrument is established. This method will allow a better age-estimation of undated assemblages with determinable microliths, but probably will also be applicable to other periods and artefact groups.

In our case the frequencies of the following microlith types represent – with decreasing strength – sensible chronological markers: C022 (34.9 %), D021 (33 %), D023 (30.3 %), C027 (24.7 %), D022 (23.8 %), C031 (20.8 %), C010 (17.1 %), D028 (15.5 %) and E040 (14.4 %). Additionally, some of the rare types, such as two further lancet points (C034 and C036) and five base retouched micro points (C23j; C125; C221; C225; C228) are relevant for the chronological setting as well.

Furthermore, the constraint correspondence analysis of the microlithic types from Mesolithic sites of an area of appox. 300.000 square kilometres between the North Sea, the upper Danube and the northern central European plain reveal that microlithic types are not the only important indicators of chronological phases. As reflected in the distances between the assemblages from different regions in the triplot (**Fig. 7a**), the CCA presented here shows a certain geographical sorting which we shall verify in future applications of CCA using geographical coordinates as constraints. Although already during the later Preboreal regional traditions are obvious, a further remarkable differentiation of the Mesolithic inhabitants of Central Europe into regional groups must have taken place towards the end of this chronozone. Additionally, we like to emphasize that applications of a CCA model are not limited to chronological questions but allows to estimate values of unknown constraints in any multivariate causal relationship and for causal variables of any kind. One future application may well be to describe different cultural traditions from a regional perspective while also respecting chronology as the treeplot in **Fig. 6** and **Fig. 7a** respectively shows.

Appendices

A Typology of the microliths used for the CCA.

B C14-dates for the sites/layers used for the CCA.

C Data sheet used for the CCA.

D Script for conducting the CCA in 'R'.

Note

The free open source statistical programming software 'R' and the extension package '*vegan*' are available from the 'Comprehensive R Archiv Network' (CRAN) at cran.r-project.org.

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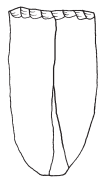
Appendix A − Typology of the microliths used for the CCA

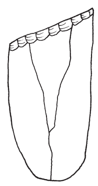
Non-geometric microlithes - Nichtgeometrische Mikrolithen

<table>
<tr><th colspan="5">Endretouched microliths</th></tr>
<tr><th>type code</th><th>name / description</th><th>sketch</th><th>remarks</th><th>dating / frequency</th></tr>
<tr><td>A010</td><td>Microlith with transverse retouch

Mikrolith mit Querretusche

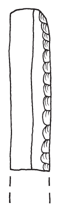
Microlith with straight end retouching (dorsal or ventral)</td><td></td><td>Microliths on small flakes or bladlets; Gramsch 1973, p. 20; Taute 1971 = type A37; G.E.E.M. 1972, Lamelle tronquée</td><td rowspan="2">Entire Mesolithic / rare</td></tr>
<tr><td>A020</td><td>Microlith with oblique retouch

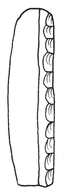
Mikrolith mit schräger Endretusche

Differentiation from microlithic points by tip angle 60° and larger. The tip lies on the unretouched edge</td><td></td><td>Microliths on small flakes or bladlets.

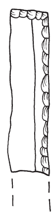
Corresponds to type 90 in Petersen 1993 = large microlith with oblique end retouching; Gramsch 1973, p. 20; Taute 1971 = type A38; G.E.E.M. 1972, Lamelle tronquée</td></tr>
<tr><th colspan="5">Backed bladelets</th></tr>
<tr><th>type code</th><th>name / description</th><th>sketch</th><th>remarks</th><th>dating / frequency</th></tr>
<tr><td>B011</td><td>Broken simple backed bladelet

Gebrochenes einfaches Rückenmesser

The fracture is clearly intentional (e.g. retouching over fracture or fracture with bulbus).</td><td></td><td>Taute 1971 = type A33</td><td rowspan="3">Entire Mesolithic / rare; more frequent during the Middle Mesolithic</td></tr>
<tr><td>B012</td><td>Complete simple backed bladelet

Vollständiges einfaches Rückenmesser</td><td></td><td>Taute 1971 = type A32</td></tr>
<tr><td>B021</td><td>Broken backed bladelet with one truncation

Gebrochenes Rückenmesser mit einem retuschierten Ende

The fracture is clearly intentional (e.g. retouching over fracture or fracture with bulbus. One end is retouched straight or obliquely.</td><td></td><td>Taute 1971 = type A35</td></tr>
</table>

General remarks:

In contrast to many Late Palaeolithic pieces, the Mesolithic backed bladlets are shorter and very narrow, i.e. made on micro blades.

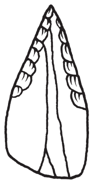
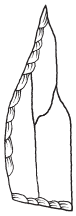
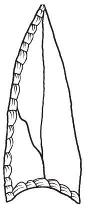
Im Gegensatz zu vielen Stücken aus dem Spätpaläolithikum sind die mesolithischen Rückenmesser kürzer und schmal, d.h. sie wurden an Mikroklingen gefertigt.

Micro points without or with dorsal basal retouch **Mikrospitzen ohne oder mit dorsaler Basisretusche**				
type code	***name*** **/ description**	**sketch**	**remarks**	**dating / frequency**
C010	*Micro point with oblique retouch* *Mikrospitze mit Schrägretusche* Microliths with a more or less oblique retouching of an end, which converges with the sharp edge in a point. The point angle is between 40° and 60.		Microliths on small flakes or bladelets; Taute 1971 = type A38; G.E.E.M. 1972 = Pointe à troncature oblique	Points with diagonal retouching have been known since the Late Palaeolithic (Ahrensburgian culture). Here they are called Zonhoven points, but they were exclusively made on blades. The Mesolithic objects are known from the beginning of this period, but are more frequent during the Initial and Early Mesolithic.
C011	*In outline triangular micro blade with diagonally retouched short end* *Im Umriss dreieckige Klinge mit schräg retuschiertem kurzem Ende* Obliquely truncated micro blade with two converging, more or less pointed unretouched edges.		Petersen 1993 = type 101	Early and Middle Mesolithic / more frequent in the Middle Mesolithic; in Denmark entire younger Maglemose period, particularly often in Phase 5, but also occurs in the oldest Kongemose period (Blak phase).
C021	*Micro point with complete retouching of one edge* *Mikrospitze mit kompletter Retuschierung einer Kante* Due to the straight or arched dorsal retouching of an edge a point has been worked out. The point angle is smaller than 40°. The width of the piece is greater than one third of the length.		Fine point A after Gramsch 1973 (following Bohmers and Wouters 1956, 29); Petersen 1993 = type 91; Taute 1971 = type A1; G.E.E.M. 1972 = pointe à retouche laterale	Entire Mesolithic / These points are known from the beginning of the Mesolithic, but are more frequent during the Early Mesolithic.
C22	*Partially edge-retouched micro point* *Mikrospitze mit partieller Retuschierung einer Kante*		Fine point B after Gramsch 1973 (following Bohmers and Wouters 1956, 29); Taute 1971 = type A2; G.E.E.M. 1972 = Pointe à troncature très oblique	Entire Mesolithic / These points are known from the beginning of the Mesolithic, but are more frequent during the Initial and Early Mesolithic.
C22g	*Partially edge-retouched micro point with straight base retouch* *Partiell kantenretuschierte Mikrospitze mit gerader Basisretusche*		Definition by N. Schneid (2014)	Middle Mesolithic / rare

General remarks:

If not mentioned otherwise, the tips always lie on the central axis.

Wenn nicht anders erwähnt, liegen die Spitzen immer auf der Mittelachse.

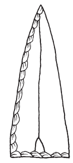
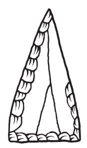
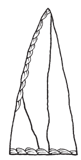
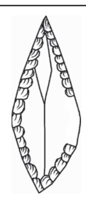
Micro points without or with dorsal basal retouch **Mikrospitzen ohne oder mit dorsaler Basisretusche**				
type code	***name*** **/ description**	**sketch**	**remarks**	**dating / frequency**
C22j	*Micro point with partial retouching on both edges* *Mikrospitze mit zwei partiell retuschierten Kanten*		Definition by N. Schneid (2014)	Middle Mesolithic / rare
C023	*Micro point with complete retouching of one edge and dorsal oblique base retouch* *Mikrospitze mit kompletter Retuschierung einer Kante und dorsaler schräger Basisretusche*		The base retouching can be straight or concave; definition by N. Schneid (2014)	Early and Middle Mesolithic / frequent
C23j	*Micro point with complete retouching of one edge, partial retouch on the second edge and dorsal oblique base retouch* *Mikrospitze mit kompletter Retuschierung einer Kante, partieller Retuschierung der gegenüberliegenden Kante und dorsaler schräger Basisretusche*		Definition by N. Schneid (2014)	Middle Mesolithic / rare
C024	*Partially edge-retouched micro point with dorsal oblique base retouch* *Partiell kantenretuschierte Mikrospitze mit dorsaler schräger dorsaler Basisretusche*		The base retouching can be straight, convex, or concave. Fine point C after Gramsch 1973 (following Bohmers and Wouters 1956, 29)	Middle Mesolithic / frequent
C025	*Micro point with complete retouching of one edge and dorsal concave base retouch* *Komplett kantenretuschierte Mikrospitze mit konkaver dorsaler Basisretusche*		Fine point C after Gramsch 1973 (following Bohmers and Wouters 1956, 29), Taute 1971 = type A5; G.E.E.M. 1972 = pointe à base transversale	Early and Middle Mesolithic / more frequent during the Middle Mesolithic

General remarks:

If not mentioned otherwise, the tips always lie on the central axis.

Wenn nicht anders erwähnt, liegen die Spitzen immer auf der Mittelachse.

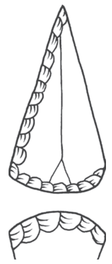
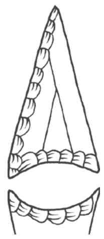
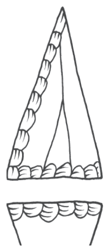
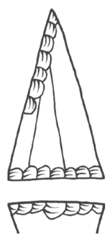
Micro points with dorsal basal retouch
Mikrospitzen mit dorsaler Basisretusche

type code	*name* / definition	sketch	other characteristics or remarks	dating / frequency
C026	*Partially edge-retouched micro point with dorsal concave base retouch* *Partiell kantenretuschierte Mikrospitze mit dorsaler konkaver Basisretusche*		Fine point C after Gramsch 1973 (following Bohmers and Wouters 1956, 29); G.E.E.M. 1972 = pointe à base transversale	Middle Mesolithic / rare
C027	*Micro point with complete retouching of one edge and dorsal straight base retouch* *Komplett kantenretuschierte Mikrospitze mit gerader dorsaler Basisretusche*		Taute 1971 = type A4; G.E.E.M. 1972 = pointe à base transversale	Middle Mesolithic / frequent
C27k	*Partially edge-retouched micro point and dorsal convex base retouch* *Partiell kantenretuschierte Mikrospitze mit dorsaler konvexer Basisretusche*		Definition by N. Schneid (2014)	Early and Middle Mesolithic / rare
C27j	*Micro point with complete retouching of one edge, partial retouch on the second edge and dorsal straight base retouch* *Mikrospitze mit kompletter Retuschierung einer Kante, partieller Retuschierung der gegenüberliegenden Kante und dorsaler gerader Basisretusche*		Definition by N. Schneid (2014)	Middle Mesolithic / rare
C028	*Partially edge-retouched micro point with dorsal straight base retouch* *Partiell kantenretuschierte Mikrospitze mit dorsaler gerader Basisretusche*		Definition by B. Gehlen; G.E.E.M. 1972 = pointe à base transversale	Final Early Mesolithic and Middle Mesolithic / rare
C029	*Notched micro point* *Gekerbte Mikrospitze* The tip angle is smaller or equal to 60°. The lower part of the retouched edge has a clear retouched notch.		Definition by B. Gehlen The pieces are relatively wide.	Early Mesolithic to early middle Mesolithic / rare
C210	*Micro point with rhombic outline* *Mikrospitze mit rautenförmigem Umriss* Only one side is retouched with an obtuse angle. The second side is not retouched but equally angled.		Definition by B. Gehlen	Final Early Mesolithic and Middle Mesolithic / rare
C21k	*Bilateral retouched micro point with rhombic outline* *Beidkantig retuschierte Mikrospitze mit rautenförmigem Umriss*		Definition by N. Schneid (2014)	Middle Mesolithic / rare

General remarks:

The tips always lie on the central axis.

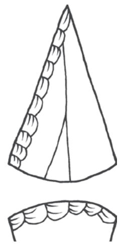
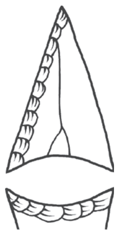
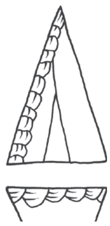
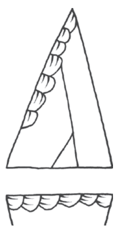
Die Spitzen liegen immer auf der Mittelachse.

Micro points with dorsoventral basal retouch Mikrospitzen mit dorsoventraler Basisretusche				
type code	***name* / description**	**sketch**	**remarks**	**dating / frequency**
C121	*Complete edge-retouched micro point with dorsoventral convex base retouch* *Komplett kantenretuschierte Mikrospitze mit dorsoventraler konvexer Basisretusche*		Taute 1971 = type A9	Early and Middle Mesolithic / more frequent in the Early Mesolithic (Beuronian A in south western Germany)
C125	*Complete edge-retouched micro point with dorsoventral concave base retouch* *Komplett kantenretuschierte Mikrospitze mit dorsoventraler konkaver Basisretusche*		Taute 1971 = type A11; G.E.E.M. 1972 = pointe à base transversale	Middle Mesolithic / frequent
C127	*Complete edge-retouched micro point with dorsoventral straight base retouch* *Komplett kantenretuschierte Mikrospitze mit dorsoventraler gerader Basisretusche*		Taute 1971 = type A10; G.E.E.M. 1972 = pointe à base transversale	Early and Middle Mesolithic / frequent
C128	*Partially edge-retouched micro point with dorsoventral straight base retouch* *Partiell kantenretuschierte Mikrospitze mit dorsoventraler gerader Basisretusche*		Definition by B. Gehlen; G.E.E.M. 1972 = pointe à base transversale	Early and Middle Mesolithic / rare

General remarks:

The tips always lie on the central axis.

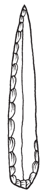
Die Spitzen liegen immer auf der Mittelachse.

Micro points with ventral basal retouch **Mikrospitzen mit ventraler Basisretusche**				
type code	***name*** **/ definition**	**sketch**	**remarks**	**dating / frequency**
C221	*Complete edge-retouched micro point with ventral convex base retouch* *Komplett kantenretuschierte Mikrospitze mit ventraler konvexer Basisretusche*		Taute 1971 = type A6	Middle Mesolithic / rare
C225	*Complete edge-retouched micro point with ventral concave base retouch* *Komplett kantenretuschierte Mikrospitze mit ventraler konkaver Basisretusche*		Taute 1971 = type A8; G.E.E.M. 1972 = pointe à base transversale	Middle Mesolithic / rare
C227	*Complete edge-retouched micro point with ventral straight base retouch* *Komplett kantenretuschierte Mikrospitze mit ventraler gerader Basisretusche*		Taute 1971 = type A7; G.E.E.M. 1972 = pointe à base transversale	Final Early Mesolithic / Middle Mesolithic / rare
C228	*Partially edge-retouched micro point with ventral straight base retouch* *Partiell kantenretuschierte Mikrospitze mit ventraler gerader Basisretusche*		Definition by B. Gehlen	Middle Mesolithic / rare

General remarks:

The tips always lie on the central axis.

Die Spitzen liegen immer auf der Mittelachse.

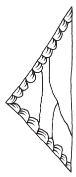
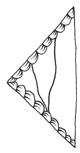
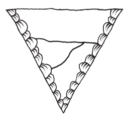
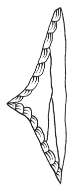
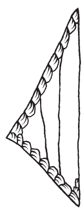
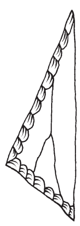
Lancet points **Lanzettspitzen**				
type code	***name* / description**	**sketch**	**remarks**	**dating / frequency**
C031	*Edge-retouched lancet point* *Kantenretuschierte Lanzettspitze* Elongated and narrow point with regular, curved or straight, complete retouching of one edge		Gramsch 1973 = Lancet point; G.E.E.M. 1972 = pointe à dos rectiligne	Middle Mesolithic / more frequent during the later Middle Mesolithic
C033	*Lancet point with dorsal straight or convex base retouch and additional partial retouching on the second edge* *Lanzettspitze mit dorsaler gerader oder konvexer Basisretusche und zusätzlicher partieller Retusche an der zweiten Kante*		Gramsch 1973 = Lancet point; G.E.E.M. 1972 = pointe à dos rectiligne	Middle Mesolithic / rare
C034	*Lancet point with partial edge retouching and dorsally retouched straight oblique base* *Lanzettspitze mit partieller Kantenretusche und dorsal retuschierter gerader schräger Basis* Elongated and narrow lace with partial edge retouching and retouching in the lowest third of the opposite edge, which merges into a straight or diagonal base retouch.		Petersen 1993 = type 92	Middle Mesolithic / rare; in Denmark: Maglemose, phase 2 / frequent
C036	*Lancet point with dorsal concave and oblique retouched base* *Lanzettspitze mit dorsaler konkaver, schräg retuschierter Basis* Long and narrow point with complete edge retouching and subsequent oblique, concave base retouch.		Petersen 1993 = type 94 Such forms differ from uneven-sided triangles in this way, that the tip lies on the central axis.	Middle Mesolithic / rare; in Denmark: Maglemose / frequent
C037	*Lancet point with partial edge retouching* *Lanzettspitze mit partieller Kantenretusche* Elongated and narrow point with regular, curved or straight, partial retouching of one edge.		Defined on Friesack 4 material (B. Gehlen)	Late Early and Middle Mesolithic / frequent
C038	*Lancet point with partial edge retouching and dorsal oblique retouched base* *Lanzettspitze mit partieller Kantenretusche und schräger dorsal retuschierter Basis*		Defined on Friesack 4 material (B. Gehlen)	Late Early and Middle Mesolithic / rare
C042	*Lancet point in the shape of a long trapezium* *Lanzettspitze in Form eines langgestreckten Trapezes* Trapezoidal, elongated and narrow tip. The assumed angle between the two retouched ends (Schenkelwinkel after Taute 1971) is obtuse.		Defined on Friesack 4 material (B. Gehlen)	Middle Mesolithic / rare

General remarks:

Lancet points are at least three times as long as they are wide. The tip of lancet points always lies on the central axis.

Lanzettspitzen sind mindestens dreimal so lang wie breit. Die Spitze liegt immer auf der Mittelachse.

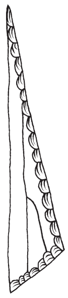
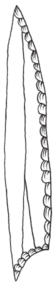
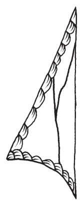
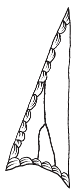
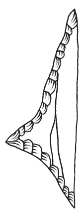
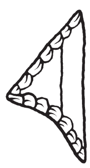
Geometric microlithes - Geometrische Mikrolithen

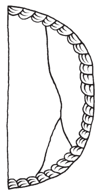
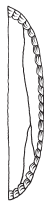
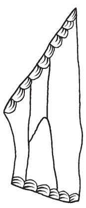
Triangles, part 1 Dreiecke, Teil 1				
type code	***name* / description**	**sketch**	**remarks**	**dating / frequency**
D011	*Isosceles obtuse triangle* *Gleichschenklig-stumpfwinkliges Dreieck* The angle between the two retouched sides is more than 90°		Petersen 1993 = type 96; Taute 1971 = type A17; G.E.E.M. 1969 = triangle isocèle	Large isosceles obtuse triangles and Clearly unequal triangles (s.b. type D021) have been known since the Late Palaeolithic (Ahrensburg culture). The Mesolithic objects are known from the beginning of this period, but are more frequent during the Early Mesolithic
D012	*Isosceles right-angled triangle* *Gleichschenklig-rechtwinkliges Dreieck* The angle between the two retouched sides is 90°		Taute 1971 = type A18	Early Mesolithic / rare
D013	*Isosceles pointed triangle* *Gleichschenklig-spitzwinkliges Dreieck* The angle between the two retouched sides is less than 90°		Taute 1971 = type A19. Taute regards this type as a transverse arrowhead	Middle Mesolithic, typical for the Beuronian B / rare
D014	*Prejlerup-triangle* *Prejlerup-Dreieck* Slender triangle with retouched edges of equal length, which meet in a prominent tip (like a lug)		Petersen 1993 = type 97	Middle Mesolithic / rare; In Denmark: Maglemose, phase 2 / rare
D021	*Clearly unequal triangle* *Deutlich ungleichschenkliges Dreieck* The long retouched edge is less than twice as long as the short retouched one		Petersen 1993 = type 98; Taute 1971 = type A20; G.E.E.M. 1969 = triangle scalène	Clearly unequal triangles and Large isosceles obtuse triangles (s.a. type D011) have been known since the Late Palaeolithic (Ahrensburg culture). The Mesolithic objects are known from the beginning of this period, but are more frequent during the Middle Mesolithic; In Denmark: Maglemose, phases 0-2
D022	*Strong unequal triangle* *Stark ungleichschenkliges Dreieck* The long retouched edge is at least twice as long and at most three times as long as the short retouched one		Taute 1971 = type A21; G.E.E.M. 1969 = triangle scalène	Early and Middle Mesolithic / much more frequent during the Middle Mesolithic

General remarks:

Triangles are also considered to be isosceles if the length of the retouched sides only deviates by a maximum of 10%.

Dreiecke werden auch als gleichschenklig angesehen, wenn die Länge der beiden retuschierten Schenkel um maximal 10% differieren.

Triangles, part 2 **Dreiecke, Teil 2**				
type code	***name* / description**	**sketch**	**remarks**	**dating / frequency**
D023	*Extremely unequal triangle* *Extrem ungleichschenkliges Dreieck* The longer retouched edge is more than three times as long as the short one. Usually the pieces are relatively long. Sometimes the angle between the retouched legs is not clearly defined and the two long edges are almost parallel. Sometimes the long tip is retouched dorsally and ventrally opposite.		Elongated and slender triangles after Gramsch (1973, 21); Taute 1971 = type A22; G.E.E.M. 1969 = triangle scalene allongé à petit côte court	Middle Mesolithic / more frequent after 8100 calBC
D027	*Lancet-like Sværdborg triangle with a concave retouched short side* *Lanzettartiges Sværdborg-Dreieck mit konkav retuschiertem kurzem Schenkel* Extremely unequal triangle with a pronounced tip and a slightly curved, long retouched edge. The short edge is clearly retouched in a concave manner.		Type defined on the material of Friesack 4, complex II (B. Gehlen)	Early and Middle Mesolithic / rare
D028	*Clearly unequal triangle with concave retouched short side* *Deutlich ungleichschenkliges Dreieck mit konkav retuschiertem kurzen Schenkel*		Defined on Friesack 4 material (B. Gehlen)	Middle Mesolithic / frequent
D029	*Strong unequal triangle with concave retouched short side* *Stark ungleichschenkliges Dreieck mit konkav retuschiertem kurzen Schenkel*		Defined on Friesack 4 material (B. Gehlen)	Middle Mesolithic / rare
D031	*Clearly unequal triangle with lateral spine* *Deutlich ungleichschenkliges Dreieck mit lateralem Dorn*		Defined on Friesack 4 material (B. Gehlen); similar to type D014	Middle Mesolithic / rare
D110	*Isosceles triangle with one concave retouched side* *Gleichschenkliges Dreieck mit einem konkaven Schenkel*		Definition by B. Gehlen	Middle Mesolithic / rare

Segments **Segmente**				
type code	***name*** **/ description**	**sketch**	**remarks**	**dating / frequency**
E020	*Symmetrical segment* *Symmetrisches Segment* The course of the steep or half-retouched edge corresponds to a curve section. The length-to-width ratio is between 2:1 and 4:1		Taute 1971 = type A16; G.E.E.M. 1969 = segment de cercle	Early and Middle Mesolithic / rare
E040	*Elongated symmetrical segment* *Langschmales symmetrisches Segment* The length-to-width ratio is 4:1 or larger		Defined on Friesack 4 material (B. Gehlen)	Middle Mesolithic / frequent
Squares **Vierecke**				
type code	***name*** **/ description**	**sketch**	**remarks**	**dating / frequency**
F25	*Elongated trapeze on irregular blade* *Langschmales Trapez aus unregelmäßiger Klinge*		Taute 1971 = type A23 The angle between the two retouched ends (Schenkelwinkel after Taute 1971) is obtuse.	Early and Middle Mesolithic / frequent
F25k	*Elongated trapeze from irregular blade with one straight and one concave retouched side* *Langschmales Trapez aus unregelmäßiger Klinge mit einem geraden und einem konkav retuschierten Schenkel*		Definition by B. Gehlen The angle between the two retouched ends (Schenkelwinkel after Taute 1971) is obtuse.	Middle Mesolithic / rare
F031	*Asymmetrical trapeze on irregular blade* *Asymmetrisches Trapez aus unregelmäßiger Klinge* Asymmetrical trapezes have two obliquely retouched ends of unequal length, the imaginary extension of which meet at an acute angle (less than 90 °).		The angles between the long unretouched edge and the retouched ends are always greater than 45 °; Taute 1971 = type A24	Early and Middle Mesolithic / rare

General remarks:

On rectangular microliths it is not the long edges of the blade that have been retouched, but the ends. Squares have a length-to-width ratio greater than or equal to 1:1, i.e. the blade length obtained is greater than the blade width. If the ratio is less than 1:1, it is a transverse arrow head.

Bei viereckigen Mikrolithen sind nicht die Längskanten der Klingen, sondern die Enden retuschiert. Viereckige Mikrolithen haben ein Längen-Breitenverhältnis größer oder gleich 1:1, d.h. die erhaltene Klingenlänge ist größer als die Klingenbreite. Ist das Verhältnis kleiner 1:1, handelt es sich um Pfeilschneiden.

Appendix B – C^{14} dates used for the CCA

site no.	site name	CCA label	lab. no.	date BP	std. dev. BP	combined BP	combined cal BC (68% prob.)	combined cal BC (95% prob.)	mean cal BC (68% prob.)	mean cal BC (95%prob.)	sample material	trench	square	layer	layer complex	chrono-zone	references
1	Friesack 4	F43c	Bln-3354	8700	70	-	-	-	7699	7873	charcoal	Z	F3	15	IIIc	early Boreal	Görsdorf & Gramsch 2004, 310
		F43b	Bln-3021	9010	70	8958 ± 27	8252-8016	8275-7967	8134	8121	charcoal	Z	F4	16	IIIb		Gramsch 2000, 61
			Bln-3002	9030	60								C8	33			
			Bln-3003	8940	60								C8	32b			
			Bln-3006	9000	70								D7	32b			
			Bln-3010	8810	70								F6	5a			
			Bln-3028	8940	60								F9	5a			
		F43a	Bln-3011	8840	60	8998 ± 22	8269-8234	8285-8211	8265	8248	charcoal	Z	F6	6a	IIIa		
			Bln-3012	8960	60								F6	5b			
			Bln-3022	9150	70								F4	5b			
			Bln-3013	8980	60								F6	6b			
			Bnl-3023	9040	60								F4	6b			
			Bln-3014	8980	60								F6	6c			
			Bln-3017	9010	70								F2	6c			
			Bln-3008	9040	70								A7	6c			
			Bln-3027	9040	70								F8	6c			
		F42d	Bln-3024	9180	70	9210 ± 50	8536-8333	8556-8296	8434	8426	charcoal	Z	F4	17	IId	late Preboreal	
			Bln-3009	9240	70								A7	17			
		F42c	Bln-3706	9470	60	9368 ± 25	8703-8566	8732-8557	8635	8645	charcoal	C	F5	23a	IIc		Görsdorf & Gramsch 2004, 310
			Bln-3705	9420	80								F5	23a			
			Bln-3358	9400	70								F5	23f			
			Bln-3355	9380	70								F8	23o			
			Bln-3603	9350	70								H6	23d			
			Bln-3297	9340	60								D3	23a			
			Bln-3359	9340	70								F4	23g			
			Bln-3356	9220	70								F5	23b			
		F42b	Bln-3018	9400	70	-	-	-	8665	8790	charcoal	Z	F2	8a	IIb		Gramsch 2000, 61
		F42a	Bln-3000	9220	60	9271 ± 46	8612-8429	8628-8333	8521	8481	charcoal	Z	F1	8b	IIa		
			Bln-3025	9340	70								F4	8b			
		F41c	Bln-3019	9640	70	-	-	-	9042	9031	charcoal	Z	F2	9a	Ic	middle Preboreal	
		F41b	Bln-3020	9640	60	9610 ± 43	9160-8845	9224-8819	9003	9022	charcoal	Z	F2	9b			
			Bln-3001	9580	60								F1	13	Ib		
		F41a	Bln-3026	9670	60	-	-	-	9062	9048	charcoal	Z	F4	10a	Ia		

site no.	site name	CCA label	lab. no.	date BP	std. dev. BP	combined BP	combined cal BC (68% prob.)	combined cal BC (95% prob.)	mean cal BC (68% prob.)	mean cal BC (95% prob.)	sample material	layer	chrono-zone	references
2	Achim, Bierden 30	Abi	AAR-15901	9586	41	9600 ± 32	9146-8845	9205-8821	9000	9013	charcoal	-	middle Preboreal	Gerken 2013, 372
			Poz-43938	9620	50									
3	Haverbeck	Habe	Hv-23306	9425	105	-	-	-	8834	8757	charcoal	hearth 1	middle Preboreal	Tolksdorf 2008, 101
4	Duvensee WP 9	Du9	KI-3041	9590	90	9493 ± 43	9114-8713	9122-8635	8914	8879	charcoal	-	middle Preboreal	Holst 2014, Tab. 4
			KI-3042	9380	80									
			KI-3043	9600	90									
			KI-3044	9440	80									
5	Duvensee WP 8	Du8	KI-1818	9640	100	9496 ± 58	9117-8654	9129-8629	8886	8879	birch bark mat	-	middle Preboreal	Holst 2014, Tab. 4
			KI-1819	9410	110									
			KI-1885.01	9420	130						hazelnut shells			
			KI-1885.03	9440	130						charcoal			
6	Duvensee WP 2	Du2	KI-1884.01	9420	130	9333 ± 80	8728-8464	8789-8315	8596	8552	charcoal	-	late Preboreal	Holst 2014, Tab. 4
			KI-1884.02	9280	100						hazelnut shells			
7	Duvensee WP 1	Du1	KI-1883.01	9200	160	9160 ± 84	8531-8289	8612-8246	8410	8429	charcoal	-	early Boreal	Holst 2014, Tab. 4
			KI-1883.02	9170	120						hazelnut shells			
			H-431/379	9095	170						hazelnut shells			
8	Duvensee WP 8	Du6	KI-1111	9100	130	8993 ± 71	8291-8012	8331-7944	8152	8138	hazelnut shells	-	early Boreal	Holst 2014, Tab. 4
			KI-1112	8840	110									
			KI-1113	9090	130									
9	Duvensee WP 9	Du13	KI-2125	8630	160	8709 ± 55	7775-7600	7943-7594	7688	7769	charcoal	-	late Boreal	Holst 2014, Tab. 4
			KI-2126	8700	80									
			KI-2378	8740	85									
10	Rieger Busch	RiB	MAMS-14123	9333	36	-	-	-	8596	8589	charcoal (*salix*)	-	late Preboreal	Schneid 2013
11	Oelde-Weitkamp 2	OW2	GrA-48906	8845	45	-	-	-	8004	7987	hazelnut shell	-	early Boreal	Arndt 2012

site no.	site name	CCA label	lab. no.	date BP	std. dev. BP	combined BP	combined cal BC (68% prob.)	combined cal BC (95% prob.)	mean cal BC (68% prob.)	mean cal BC (95% prob.)	sample material	layer	chrono-zone	references
12	Jägerhaushöhle	Jä10	B-946	8840	70	-	-	-	8005	7961	charcoal	10	early Boreal	Oeschger & Taute 1978, 17
		Jä13	B-948	9600	100	-	-	-	9012	8984	charcoal	13	middle Preboreal	
13	Niederweimar 6	Niw6	UtC-7226	9580	60	-	-	-	8978	8995	charcoal *pinus sylvestris*	-	middle Preboreal	Schön 2015, 31
14	Rottenburg-Siebenlinden 1	RS1-2	ETH-7544	8540	75	8685 ± 55	7737-7600	7940-7589	7669	7765	bone	AH 2	middle Boreal	Kind 2003, Tab. 1
			ETH-8266	8840	80						bone			
15	Abri Bettenroder Berg IX	BB10	KN-4148	8750	220	8780 ± 156	8169-7607	8269-7585	7888	7927	charcoal	10	middle Boreal	Grote 1994, 63
			KN-4150	8810	220						charcoal			
		BB13	KN-4152	8940	220	-	-	-	8021	8139	charcoal	13	early Boreal	Grote 1994, 56
16	Rottenburg-Siebenlinden 3-5	RS3-5	ETH-14246	8705	75	8777 ± 32	7941-7749	8161-7611	7845	7886	bone	AH IV	middle Boreal	Kind et al. 2012, Tab. 12
			ETH-14248	8680	75						bone			
			ETH-32111	8730	70						bone			
			ETH-33045	8710	90						charcoal			
			ETH-26386	8875	75						bone			
			ETH-26387	8940	75						bone			

site no.	site name	CCA label	lab. no.	date BP	std. dev. BP	combined BP	combined cal BC (68% prob.)	combined cal BC (95% prob.)	mean cal BC (68% prob.)	mean cal BC (95% prob.)	sample material	layer	chrono-zone	references
17	Oostwinkel-Mostmolen (B)	OstM	UtC-3438	9250	160	-	-	-	8497	8572	hazelnut shells	-	late Preboreal / early Boreal	Crombé 1998, 4
18	Trou Al'Wesse (B)	W4bb	Beta-224152	9240	40	-	-	-	8450	8456	hazelnut shells	4 beta	early Boreal	Miller et al. 2012, 119
		W4bg	Beta-224153	9130	40	-	-	-	8350	8402	hazelnut shells	4 gamma	early Boreal	Miller et al. 2012, 119
19	Neerharen - De Kip (B)	NeKi	Lv-1092	9170	100	-	-	-	8414	8464	hazelnut shells	-	early Boreal	Lauwers & Vermeersch 1982, 34
20	Abri Kalekapp 2 (L)	Ka2-2	Beta-255824	9180	50	9211 ± 23	8531-8344	8542-8306	8438	8424	hazelnut shells	2	early Boreal	Leesch 2011, 113
			Beta-254431	9200	50						charcoal			
			Beta-254432	9140	50						hazelnut shells			
			Beta-254433	9150	50						charcoal			
			Beta-254434	9380	50						hazelnut shells			
21	Haelen-Broekweg (NL)	HaB	KIA-17631	9020	50	9042 ± 34	8286-8251	8296-8231	8269	8264	hazelnut shells	-	early Boreal	Bats et al. 2010
			KIA-17612	9060	45						hazelnut shells			
22	Abri „Auf den Leien“ near Hersberg (L)	Heb	Beta-279467	8760	50	8768 ± 39	7942-7739	8160-7606	7841	7883	hazelnut shells	U.S. 6	middle Boreal	Valotteau et al. 2009
			Beta-279468	8780	60						hazelnut shells			
23	Doel „Deurganckdok“ (B)	DD	KIA 24454	8485	40	8692 ± 27	7716-7606	7758-7596	7761	7677	hazelnut shells	-	middle Boreal	Crombé 2009, 102-103
			KIA 24034	8630	60						hazelnut shells			
			KIA 30962	8965	45						hazelnut shells			

Appendix C – Data sheet used for the CCA

name	C225	C220	C034	C036	C23j	C228	C125	D023	D013	C21k	C031	C027	F023	C27j	C011	E040	C033	C024	D029	D028	D031	D022	D110	C22g	D021	C023	C025
DD	1	0	0	0	0	0	0	1	0	1	3	0	0	0	0	3	0	2	0	0	0	0	0	0	4	2	0
RS12	0	1	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	1	0	0	0	1	1	0	2	0	1
Du13	0	0	1	2	1	0	0	3	0	0	5	0	0	0	0	0	0	1	0	1	0	8	0	1	14	2	0
F43c	0	0	0	0	0	0	0	12	0	0	6	1	0	0	0	4	0	0	0	2	1	12	0	0	26	4	2
Heb	0	1	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	1	0	0
RS34	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1	0	1	2	0	2	0	0
BB10	1	1	0	0	0	1	0	6	0	1	0	4	1	1	4	3	0	1	0	0	0	4	0	1	8	4	0
Jä10	0	0	0	0	0	0	3	0	0	0	0	2	0	0	0	0	0	0	0	1	0	0	0	0	1	0	1
Jä11	0	0	0	0	0	1	3	0	2	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3
OW2	1	1	0	0	2	0	0	0	0	0	2	2	0	0	0	4	1	0	0	0	0	1	4	0	8	0	4
F43b	0	0	1	2	0	0	0	6	0	0	11	5	0	0	4	11	2	3	7	29	0	42	0	0	95	9	15
Du6	0	0	0	0	0	0	0	0	0	0	0	3	1	0	0	0	0	0	2	7	0	6	2	0	46	1	7
BB13	0	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	4	0	0
F43a	0	0	0	0	0	0	0	0	0	0	3	1	0	0	0	2	0	0	0	0	1	7	0	0	8	1	2
HaB	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	1
Ka22	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	1	0	1	0
F42d	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	3	1	0	11	0	0
Du1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0
W4bb	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
W4bg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
Reih	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0
NeKi	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
Du2	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	5	0	0	9	5	0
OstM	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	3	0	1	0	0	0	0	0	0	0	0	1
RiB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0
F42c	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
F42b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	2	0	0	3	1	2
Habe	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Du8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Du9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Jä13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Niw6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1
Abi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
F41c	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	3	0	0
F41b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
F41a	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0

name	C026	F025	C210	C042	C028	B	E020	C227	D012	C27k	D011	C037	C021	C22j	C127	A	C010	F031	C128	C038	D014	D027	C120	C022	C029	calBC
DD	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7677
RS12	0	0	1	0	0	4	1	1	2	1	2	0	0	0	0	0	2	0	0	0	0	0	1	3	0	7765
Du13	0	2	0	1	0	0	0	0	0	0	4	0	3	0	0	0	2	0	0	0	0	0	0	1	0	7769
F43c	0	2	0	0	0	0	2	0	0	0	7	4	11	0	0	3	4	0	0	0	0	2	0	9	0	7873
Heb	0	0	0	0	0	2	0	0	0	1	1	0	0	0	2	0	1	0	0	0	0	0	0	0	0	7883
RS34	1	0	0	0	0	0	0	0	2	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	7886
BB10	0	3	0	0	1	5	3	1	2	1	3	0	7	1	1	3	17	0	1	0	0	0	2	5	0	7927
Jä10	1	0	0	0	0	0	0	0	0	0	2	0	2	0	1	0	0	0	0	0	0	0	0	6	0	7961
Jä11	1	0	0	0	0	0	0	0	3	0	0	0	1	0	4	2	3	0	0	0	0	0	0	1	0	0
OW2	0	1	0	1	0	0	2	0	0	0	0	3	6	0	0	1	1	0	0	0	0	0	0	2	1	7987
F43b	3	10	0	3	1	4	9	0	0	0	39	3	29	0	0	17	18	1	0	1	1	0	0	35	1	8121
Du6	1	2	0	0	0	1	2	0	3	0	13	0	6	0	0	3	13	4	0	0	0	0	0	8	0	8138
BB13	0	1	0	0	1	2	2	0	1	0	1	0	2	0	0	4	2	0	0	0	0	0	0	1	0	8139
F43a	0	1	0	0	1	0	2	0	0	0	4	1	2	0	0	0	0	0	0	0	0	1	0	5	1	8248
HaB	0	1	0	0	0	2	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	3	0	8264
Ka22	0	0	0	0	1	4	2	0	0	1	1	0	3	0	1	0	2	0	0	0	0	0	0	12	0	8424
F42d	1	1	0	0	0	1	0	0	0	0	0	2	0	0	0	3	7	0	0	0	1	0	0	2	1	8426
Du1	0	0	0	0	1	1	0	0	0	0	4	0	3	2	0	3	14	0	0	0	0	0	0	8	0	8429
W4bb	0	0	0	0	0	1	0	0	5	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	8456
W4bg	0	0	0	0	0	1	0	0	3	2	0	0	3	0	0	0	0	0	0	0	0	0	0	2	0	8402
Reih	0	0	0	0	0	0	3	1	0	1	3	0	4	0	1	0	0	0	0	0	0	0	0	7	0	0
NeKi	0	0	0	0	0	6	0	0	0	0	3	1	4	0	0	0	0	0	0	0	0	0	0	11	0	8464
Du2	0	1	0	3	1	0	0	0	1	0	3	0	3	0	0	0	7	2	0	0	0	0	0	0	3	8552
OstM	0	0	1	0	0	4	0	2	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	8	0	8572
RiB	0	0	0	0	1	2	0	0	0	1	1	4	5	0	2	1	0	0	0	0	0	0	0	7	0	8589
F42c	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2	0	0	0	0	0	0	0	0	8645
F42b	0	0	0	0	0	0	1	0	0	0	2	3	0	0	0	0	2	0	0	1	0	0	0	7	1	8790
Habe	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	10	0	8757
Du8	0	0	0	0	0	0	2	0	0	0	0	0	11	0	0	0	10	0	0	0	0	0	0	40	0	8879
Du9	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	5	3	0	0	0	0	0	0	26	0	8879
Jä13	0	4	0	0	0	0	0	0	4	1	19	0	1	0	4	7	7	0	1	0	0	0	4	1	0	8984
Niw6	0	2	0	0	0	1	1	0	0	0	1	0	8	0	1	2	9	0	0	0	1	0	0	6	0	8995
Abi	0	0	0	0	0	3	0	0	0	1	0	0	1	0	0	0	5	0	0	0	0	0	0	2	0	9013
F41c	0	0	0	0	0	0	1	0	0	0	1	0	2	0	0	0	1	0	0	0	0	1	0	3	2	9031
F41b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	9022
F41a	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2	4	1	0	0	0	0	0	9	0	9048

Appendix D − Script for conducting the CCA in 'R'

```
###                         CCA mesolithic data
#
# This code shows how to compute a constrained correspondence
# analysis for a data table with cases (assemblages, in rows)
# and categories (types, in columns) using a single metric
# variable as constrained. The cells of the table contain
# counts.
# In this study the rows are mesolithic assemblages of
# microliths and the columns are microlith types. The
# constraining variable is the mean of a calibrated 14C
# date of an assemblage.
#
# The aim is to order the assemblages according to the
# similarities of the their microlith spectra with special
# focus on that similarities which can be connected to the
# dates. This relation is tested (by a permutation) to make
# sure there really is a signal in the microlith data that
# is connected to the 14C dates.
#
# Finally the established relation is used in a new way.
# Instead of solving a formula like "given that age, how
# does the spectrum look like" now the direction of analysis
# is reversed and the formula just established is turned
# round and solved for "given the spectrum, what age is
# connected to it".
#
# The approach is called calibration. It is an established
# analysis in community ecology and is in use for decades.
#
#
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#
# References:
# a) method
# Ter Braak 1984; Legendre/Legendre 2012 ch. 11.2
# b) computation
# Borcard et al. 2018 ch. 6.4
# c) software R and extension package vegan
# R Core Team 2020; Oksanen et al. 2019
#
# To reproduce this approach with your own data make
# sure the data table has the same structure as ours:
```

```
# the first column contains the names, the second the
# constraint (14C date) and the third to k-th column
# abundance data (counts or presence/absence as 1/0).
# In the later cells all values are integers. No row
# or column name has a blank space. Missing values of
# the constraint are coded as 0 not as NA.


###     1. Extension Package and Data Preparation

##      1.1. Package and Preparations

# Beware! Workspace will be emptied at start:

rm(list=ls())            # clear workspace

ls()                     # workspace is empty

options(scipen=10)       # show decimals up to 10th

# The R extension package vegan can be considered
# to be 'The Queen of Multivariate Analysis' for R.

# The next line is necessary only the 1st time,
# this code is run in your R software.

if(!require(vegan)) install.packages("vegan")

# checks if package vegan is installed and
# runs the installation if necessary

# Necessary every time:

require(vegan)           # load extension package "vegan"


##      1.2. Data Import and Preparation

#       1.2.1. Import Data Table

# Import a data table stored as a .csv file into R:
# read a semicolon separated (ascii) data table file
# with column names (header=TRUE), row names in first
# column (row.names=1) and semicolon as separator
# (sep=";") as R data frame object - here named dat.
```

```
dat <- read.table(file.choose(), header=TRUE, sep=”;”,
                        row.names=1)

# Function “file.choose()” opens the import window;
# We select our data table “202011_meso_cca_time_data.csv”.

# Note, there are no white spaces in the row or column
# names nor the data.

# Inspect the data by indexing rows and columns 1 to 5.

dat[1:5,1:5]            # shows first 5 lines and 5 columns

str(dat)                # checks structure

# ‘data.frame’:   36 obs. of  54 variables:
# $ F021 : int  0 1 0 0 0 0 0 0 0 0 ...
# $ C225 : int  1 0 0 0 0 0 1 0 0 1 ...
# $ C220 : int  0 1 0 0 1 0 1 0 0 1 ...
# [output truncated]

# There 36 assemblages (rows) and 53 variables. 52 with
# counts of microlith types and column 53 with 14C dates.
# Column 1 of the .csv table is no column any more but
# used to label the rows.

# Note: all type counts (“F012” etc.) and 14C dates,
# being years, should be integer numbers i.e. a R vector
# of type integer (“int”). In case of problems check the
# data table before import.


#        1.2.2. Prepare Data for Analysis

# Extract count data (abundances) as data table object.
# Last column holds 14C dates. Function ‘ncol()’ outputs
# the number of columns, here the number 53. The combination
# of a minus sign and an integer, here 53, specifies the
# column to be removed.

abu <- dat[ , -ncol(dat)]

str(abu )               # only 52 columns, column 53 is omitted

# Note, CA or CCA do not accept empty rows or columns
# or NA values! So check data.
```

```
any(colSums(abu)==0)
any(rowSums(abu)==0)
any(is.na(abu))

# Select constraining variable

con  <- dat[ , ncol(dat)]          # choose variable column from input

# Two assemblages do not have a 14C date;
# identify and remove them.

(rem <- which(con==0))          # index numbers of rows

# Note, we coded the missing values as 0, not as NA.
# Note, a command line in brackets prints output to console.

# The assemblages are “Jägerhaushöhle, layer 11” (# 9) and
# “Reinheim” (# 21).

rownames(abu)[rem]

# Remove these elements from the data before proceeding to CCA.

counts <- abu[-rem, ]  # remove these rows from count data
                       # and asign as new data table object

calBC  <- con[-rem]    # remove these entries from constraint
                       # and asign as new integer vector

dim(counts)            # 34 rows (assemblages) and 52 columns
(types)
length(calBC)          # vector with 34 entries left

# Now extract the undated sites i.e. the rows without
# entries of the constraining variable.

(undass <- abu[rem, ])# undated assemblages

str(undass)            # data table with only 2 rows but
                       # same structure as the ‘counts’ object
```

```
###	2. Computation

# The computation requires package vegan to be loaded
# (see 1.1.).

##	2.1. CCA

# Compute CCA model (and print to console)

(mod <- cca(counts ~ calBC))		# quick and simple

# When measured by Chisquare distance - as in CA and
# CCA - only 8.8 % of assemblage dissimilarities (value
# 0.08763 in row "Constrained" and column "Proportion" )
# are related to 14C dates. This is also called explained
# inertia.

# Can this relation be brought into being by random chance?
# Test with a Monte Carlo test with 100000 permutations.

(tes <- anova(mod, permutations = how(nperm=99999), by="axis"))

# The permutaion shows the chance for a random relation
# between microlith spectra and calibrated 14C date is
# clearly smaller than 1 in 1000 i.e. the relation discovered
# by CCA is highly significant.
#
# Note, we only used one constraining variable (14C dates),
# so there is only constrained axis ("CCA1"), the rest are
# CA axes (simple symmetric CA).
#
# Note, this is NOT a traditional ANOVA, it is only called
# so in analogy to the traditional method. see

?anova.cca

##	2.2. Predicting Constraint for new Assemblages

# Remember CCA was computed without the two undated
# assemblages. Now the relation discovered by CCA is used
# to predict the constraining variable for the assemblages
# without values for this attribute (14C date) i.e. we
# use the CCA to estimate the 14C date for the two undated
# assemblages and use the relation formula established by
# the CCA of the 34 dated assemblages.
```

```
#	2.2.1. CCA Coordinates for assemblages

(undassCCA <- predict(mod, type="wa", newdata=undass, scaling=1))

# Estimate the principal coordinates (scaling 1) for the two
# undated assemblages on the constrained axis CCA1 and include
# sampling noise (type="wa"). Note, to estimate coordinates
# without sampling noise use type="lc".
# Excluding sampling noise neglects all assemblage information
# which is not connected to the constraint - therefore we
# recommend to use "wa".

# Additionally compute coordinates on unconstrained axes (CA)

undassCA <- predict(mod, type="wa", newdata=undass, scaling=1,
				model="CA")

#	2.2.2. Estimate Constraints for undated Assemblages

#		THE HEART OF THE ANALYSIS:
#		ESTIMATE 14C DATES FOR UNDATED ASSEMBLAGES

(undassBC <- calibrate(mod, newdata=undass))

# The estimate finds the value of the constraint by reversing
# the relation between assemblage composition and 14C date
# which was found by CCA.
# Any assemblage described by the same typology as the original
# data, i.e. with identically named columns, can now be
# submitted to estimate dates.

# Note, function calibrate() has NOTHING to do with
# calibrating radiocarbon dates as in OxCal e.g.
# It is used to solve the CCA model formula for rows
# with unknown constraints - our 2 undated assemblages.

round(undassBC,-2)	# estimates
round(calBC[rownames(counts)=="Jä10"],-2)		# Jaegerhaus layer 10

# We find ca. 8100 BC for "Jaegerhaushoehle layer 11" and
# ca. 8600 BC for „Reinheim". Note „Jaegerhaushoehle layer 10"
# is dated to ca. 8000 BC which makes perfect sense.

#	2.2.3. Relation between Constraint and Types

# Finally it is interesting to see how the different
```

```
# microlith types (columns with counts) are connected to
# the constraint (14C date).
# In our setting this amounts to ask, which types are
# strongly related to chronology (and in which way) i.e.
# which should be used for dating an assemblage.

# We can answer this by looking at those parts of the
# difference between the counts of each type which are
# related to the constraint.

timraw <- inertcomp(mod, prop=TRUE)[,1]   # raw values

(timper <- rev(sort(round(timraw*100,1))))

# percentage of constrained inertia (‘information’) per
# type i.e. the amount of differences between counts of
# a type which are caused by chronology measured as percent.
# E.g. 35 % of all differences between counts of C022
# are related to time, which is quite impressing.


###     3. Results

## NOTE (!) before plotting just enlarge the
## plot window using the mouse.


##      3.1. Scree Plot

# A Scree plot visualizes the partitioning of the
# dissimilarities (inertia) among the axis i.e. how
# the information of the abundance table is divided
# among the axes.

summary(mod)$cont                    # see row “Proportion Explained”

# Extract this information from the multivariate summary

(releigs <- (summary(mod)$cont)[[1]][2,])

(releigs <- round(releigs*100, 1)) # rounded percentages

# Express parts as percentages i.e. multiply by 100.
# Plot

# determining a plot limit set as the next larger 5er value
```

```
yadd <- 5 - max(releigs ) %% 5           # difference to modulo 5

(yl <- max(releigs) + yadd)              # add that difference

cols <- c(1,rep(8,length(releigs)-1))    # one 1 and rest 8s

barplot(releigs, las=2, cex.names=.7, ylim=c(0,yl),
                    width=1, space=0, col=cols)

# Note, axis lables stop at 14 but height is 15.

text(seq(0.5, length(releigs)-0.5,1), releigs+0.2, releigs,
            cex=0.75)        # labeling with values

pval <- round(tes[[4]][1]*100,3) # p-value for random chance

# further annotations

title(sub=paste("CCA in black; chance for random effect is < ",pval, " %", sep=""))

title(ylab="Percentage (%) of explained Inertia per Axis", cex.axis=.85 )

# Note, there is a lot of dissimilarity between spectra
# which is not related to time.


##       3.2. Relation between Date and Type Frequency

yli2 <- round(max(timper)+5,-1)          # plot limit

barplot(timper, las=2, cex.names=.75, ylim=c(0,yli2),
                    width=1, space=0)

text(seq(0.5, length(timper)-0.5,1), timper+0.8, timper,
            cex=0.75, font=2, srt=90)        # labeling with values

# further annotations

title(ylab="Percentage of constrained Inertia for type")

# Note there is a clear 'elbow' identifying all types
# from 'C022' down to 'E040' as strongly related to time.## 3.3. TRI-PLOT
# A triplot shows all three sets of entities:
# - assemblages (rows) as points;
#   (the closer the more similar)
# - types as points
```

```
#   (type frequency increases in that direction)
# - constraint as arrow
#   (project row onto it to reconstruct constrain value)
#
# For a detailed interpretation of a CCA triplot
# see Borcard et al. 2018, pages 175 & 258.

#        3.3.1. Coordinates

# We extract the coordinates for axis I (CCA1) and
# II (CA1) of the sites (sxy), the types (txy) and
# the constraint (cxy).
# 'scaling = 1' means: sites are ordered within
# a dissimilarity space which is spanned i.e. defined
# by types.

sxy <- scores(mod, display="sites", choices=1:2, scaling=1)
txy <- scores(mod, display="species", choices=1:2, scaling=1)
cxy <- scores(mod, display="bp", choices=1:2, scaling=1)

# One could also order types within site space
# using 'scaling = 2'.

#        3.3.2. Plot Preparations

# colours

tcol <- gray(.2, alpha=.5) # type point colour
ccol <- gray(.1, alpha=.7) # constraint arrow colour
scol <- gray(.8, alpha=.5) # site point colour
slcol <- gray(.4, alpha=.8) # site label colour

# legend texts

legtex <- c("types", "assemblages", "undated ass.", "C14 age")

# constraint

timtex1 <- paste(min(calBC), "BC")
timtex2 <- paste(max(calBC), "BC")
tim1x <- min(sxy[,1])
tim2x <- max(sxy[,1])
# plot limits

xli3 <- round(range(txy[,1])+c(-1,1),0)
```

```
yli3 <- round(range(txy[,2])+c(-1,1),0)

#         3.3.3. Plot

# step by stp for better control

plot(txy, type="n", xlim=xli3, ylim=yli3, las=1) # empty plot

segments(xli3[1],0, xli3[2],0, col=8)            # grid
segments(0, yli3[1],0,yli3[2], col=8)

# Points

points(txy, pch=22, bg=ccol, cex=.95) # types
text(txy[,1], txy[,2], rownames(txy), cex=.85, font=2, pos=3)

points(sxy, pch=21, bg=scol, cex=1.25)         # assemblages
text(sxy[,1], sxy[,2], rownames(sxy), cex=.75, font=3,
                  col=slcol,pos=3)

# Post projection of undated assemblages

ptex <- paste(rownames(undassCCA),": ",round(undassBC,-1), " BC",sep="")

points(undassCCA, undassCA[,1], pch="+", cex=3)
text(undassCCA+0.1, undassCA[,1], ptex, cex=1.1, font=2, pos=4)

# constraint as arrow
# [not used]
# arrows(0,0, cxy[1,1],cxy[1,2],length=.15, angle=15, lwd=4)
# text(cxy[1,1], cxy[1,2], "older", cex=1.5, font=2, pos=4)

# Instead values of constraint

arrows(tim1x,0,tim2x,0,code=3,angle=90,lwd=2)
text(tim1x, 0, timtex1, cex=1.5, font=2, pos=2)
text(tim2x, 0, timtex2, cex=1.5, font=2, pos=4)

# legend

legend("bottomright", pch=c(22,21,3,NA), lty=c(NA,NA,NA,1),
                  pt.bg=c(tcol, scol, 1, NA), legtex, bg="white", cex=1.2 )
```

```
##	3.4. Default triplot from vegan

plot(mod, scaling=1)

# projecting undated sites

text(undassCCA, undassCA[,1], rownames(undassCCA),
		cex=1.1, font=2)
```