SUMMARY

AIM OF THE PROJECT

The process of reorganisation in a social system is examined in the present study with a particular focus on the impact of climatic and environmental changes on this process.
In social-ecological resilience theory, reorganisation of social-ecological systems was described as one phase in an adaptive cycle which is framed by a proceeding phase of release or decline and a succeeding phase of exploitation or growth and contrasted by a conservation or consolidation phase (Holling 2001; Abel/Cumming/Anderies 2006; Rosen/Rivera-Collazoa 2012). Thus, in this terminology reorganisation equates the collapse of a system. In the present study, this phase is termed collapse, whereas reorganisation is understood as the complete process between two consolidation phases. The transition from an exploitation to a conservation phase was described as a slow progress in contrast to the other transitions which were considered as rather fast changes. A comparable discussion of a variable tempo in the process of evolution was led in biology about macro-evolutions (Simpson 1944) and punctuated equilibriums (Eldredge/Gould 1972; Eldredge et al. 2005). In this discussion, the temporal resolution of the records and the referenced scale of detail were identified as important factors to distinguish between the gradual development of evolution as a standard and »revolutionary periods« in which changes seemed cumulated and appeared rapidly (Thomson 1992; Mayr 1996). Physical adaptation is considered as a rather slow process. In contrast, communication, that maintains social networks of common behavioural patterns, enables these networks to change much faster and, therefore, also to be changed in a revolutionary process.
To be able to distinguish between slow evolutionary and fast revolutionary processes in the reorganisation of social systems (cf. Holling 2001; Walker et al. 2012), human behaviour has to be studied in a sufficiently fine-grained chronological framework. Changes in climate and environment were considered as external drivers of human behavioural change. To understand the impact of these external drivers on human behaviour, true shifts in those external systems such as alterations between stadial and interstadial periods should be selected as case studies. Therefore, only studies of Pleistocene societies make an understanding of the behavioural alterations in times of true climate change possible. Thus far, temporal resolution necessary for analysing an adaptive cycle in relation to such unambiguous climate changes is only reached at the end of the Pleistocene.
In north-western Europe, the rapid climatic and environmental changes during this Weichselian Lateglacial were related to the so-called Azilianisation process (cf. Bosinski 1989). This process refers to the transformation from the Late Pleistocene Magdalenian societies to the Azilian groups of the Lateglacial Interstadial. Based on the south-western French record, the Azilianisation was previously perceived contrastingly either as revolutionary process (Breuil 1913) or as evolutionary process (Sonneville-Bordes 1966). In this project, a detailed chronology of this process is established based on the archaeological record from north-western Europe to examine the progress of change. In particular, the two consolidation phases of the Late Magdalenian and the *Federmesser-Gruppen* (FMG) represent an ideal case study of an *in-situ* adaptive cycle in this area. North-western Europe was deserted during the Last Glacial Maximum (LGM) and afterwards only the south-western European Magdalenian expanded into this unpopulated area. A sustainable settlement was first established there during the Late Magdalenian. In this wide-spread, uniform substratum of the Late Magdalenian, acculturation processes can be excluded as causes of change. Consequently, climatic

and environmental changes were the only major external drivers. Therefore, the archaeological record is contextualised in the climatic and environmental developments of the Weichselian Lateglacial to examine these developments as potential drivers for changes in human behaviour. Further expansion into Northern Europe and increasing regionalisation subsequently led to the development of distinct traditions. Exchange between these traditions represented another potential external stimulus. Hence, the development from the Late Magdalenian to the FMG can be regarded as a last adaptation process undisturbed by acculturation influences.

CASE STUDY

Three major parts of the Weichselian Lateglacial record were examined: The climate record that often also served to establish a reliable chronostratigraphy, the environmental record, and the archaeological record of north-western Europe. A special emphasis was put on the chronology of the appearance of changes in the single domains. These changes were compared to answer the main questions relating to the tempo and mode of the social reorganisation as well as the relation of this process to the climatic and environmental development.

Climate and chronostratigraphy

Climate and chronostratigraphy are global systems and, therefore, the records to reconstruct these systems also need to be selected more globally (see Material-Climate, p. 7-30). In this study, these records are Greenland ice-core data from NGRIP in the GICC05 chronology (Andersen et al. 2004; Rasmussen et al. 2006; Svensson et al. 2008; Steffensen et al. 2008; Wolff et al. 2010), deep sea sediment stratigraphies from the Cariaco basin offshore Venezuela (Hughen et al. 2006) and the Porcupine Seabight offshore Ireland (Peck et al. 2007), and mainly European terrestrial archives. Terrestrial archives from outside Europe came only from Chinese speleothems found in the Hulu Cave (Wang et al. 2001) and the Qingtian Cave (Liu et al. 2008) and from Tasmanian Huon pines which provided a dendrochronological sequence (Hua et al. 2009). Further dendrochronological material incorporated in this project was recovered in Central Europe (Friedrich et al. 2004; Kromer et al. 2004) and, in particular, in Switzerland (Schaub et al. 2008b; Kaiser et al. 2012). In addition, several varved lake sediments were used including the Eifel Maar lakes (Zolitschka et al. 2000; Brauer et al. 2008), the northern German varved lakes (Merkt/Müller 1999), the East German Rehwiese sequence (Neugebauer et al. 2012), and two Polish varved lakes (Ralska-Jasiewiczowa et al. 1998; Goslar et al. 1999).

Since the development of climate is globally effective due to the thermohaline cycle, major changes (»events«) can be registered almost synchronously. These events are individually identifiable and can be used to construct a consistent chronostratigraphy to which other stratigraphies can be correlated on a global scale. Besides the global climate system, sub-systems and specific regions exist in which the records are more similar than on a global scale. In this study, the oxygen isotope record from a Greenland ice-core was used as a proxy to create a template for this climatic eventstratigraphy. The Greenland data reflects the climate in the sub-system of the northern hemisphere and, in particular, the North Atlantic region. This record was selected because of its continuity into the Weichselian Lateglacial and its relevance for north-western Europe that is also influenced by the North Atlantic climate. Previously defined limits of the Weichselian Lateglacial climate events were either made on other ice-core records, in other ice-core chronologies, and/or on other proxy data such as the deuterium excess (d, see p. 592; Björck et al. 1998; Lowe et al. 2008; Blockley et al. 2012). Thus, the limits of the climatic events for a template record of this study were newly defined based on oxygen isotope values (see p. 245-247; **tab. 63**). By this comparison, the onset of the Weichselian Lateglacial Interstadial (GI-1) around 14,690 years before the year 2000 A.D. (cal. b2k; **tab. 64**) was determined as the most intense climatic change in the period between 18,000 and 10,000 years cal. b2k (see p. 293-310). The second most intense climatic change was the onset of the recent warm period, the Holocene (GH), around 11,680 years cal. b2k. The onset of stadial periods such as the Lateglacial Stadial (GS-1) appeared more diffuse in this record. The limit between GI-1 and GS-1 was set to 12,770 years cal. b2k but the transition stretched over 250 years. The onset of the sub-event GS-2a was also set with some caution to 16,230 years cal. b2k because it was previously not detected in other proxies (Lowe et al. 2008). In contrast to the interstadial periods (GI-1; GH), stadials showed a great instability with generally larger amplitudes, in particular during the Late Pleistocene (GS-2). Perhaps, this increasing instability made a definition of an onset for stadials so difficult.

In general, observations and limits of the oxygen isotope eventstratigraphy were further confirmed by the records from Polish varved lakes and Chinese speleothems (see p. 319-334). The former are more similar to the Greenland ice-core records indicating the greater influence of the North Atlantic climate on these records and a decreasing influence on sites that are located farther within the Eurasian landmass. However, the chronologies of the Polish records were anchored to other chronologies and, thus, are not independent and continuous. Nevertheless, some interesting differences to the Greenland oxygen isotope record could be identified in these records. For instance, the onset of the Lateglacial Stadial (GS-1) was identifiable as a sharp and rapid event making a more precise definition of this limit possible (**tab. 66**). The Chinese records were radiometrically dated. The advantages of this type of dating is that it is punctual and, thus, independent of disturbances and that it circumvents the accumulation of counting errors that occurs in annually layered stratigraphies such as the Greenland ice-core records or the laminated sediments from the Polish lakes. However, in addition to the air temperature, the Chinese oxygen isotope records were also influenced by hydrology. This factor can offset the reaction of the record to the changes in air temperature significantly as shown by the duration of the Lateglacial sub-events (**tab. 68**). Therefore, dates for the limits in these records (**tab. 66**) should not be used to set limits of the oxygen isotope eventstratigraphy more precisely.

The isotope data of the Central European dendrochronology (CEDC) was also influenced by the hydrology and the onset of the Holocene appeared comparably delayed in this dataset as in the Hulu Cave. Thus far, the CEDC is continuous into the older part of GS-1 (Friedrich et al. 2004; Schaub et al. 2008b). It was formed by tree-ring growth patterns (Friedrich et al. 2001b). The onset of the Holocene determined by this pattern is similar to the onset of the Holocene in the oxygen isotope record from NGRIP. A connection between the CEDC and the German Lateglacial pine chronology (GLPC; Kromer et al. 2004) and the partially identical Central European Lateglacial Master chronology (CELM; Kaiser et al. 2012) was not yet established dendrochronologically due to insufficient data around the onset of the Lateglacial Stadial. Different attempts to bridge the gap were made using sequences of radiocarbon dates provided by Swiss and Tasmanian pine records (**fig. 71**; Schaub et al. 2008b; Hua et al. 2009; Reimer et al. 2009). These attempts neglected the possibility to test the position of the resulting correlation with the position of the Laacher See eruption (LSE) identified in the GLPC against the position of this tephra in other chronologies. If the GLPC and based on the identical parts the CELM are positioned according to the position of the LSE in the record from the Meerfelder Maar, the CELM record overlaps over a short period of time with the CEDC. The sequences from the Swiss and the Tasmanian records are correlative with the radiocarbon sequences of the GLPC and the CEDC in this position. With this provisional connection the dendrochronology became continuous into the early Lateglacial Interstadial. A comparison of patterns of tree-ring growth from this Lateglacial Interstadial part of the dendrochronology with the same part in the NGRIP isotope record showed significant offsets (**tab. 69**). This difference is probably again due to more numerous influences on tree-ring growth such as hydrology and overprinting of global climate by more local conditions. Consequently, a direct correlation of dendrochronological data with isotope records from Greenland in a high-resolution frame must also be considered critical.

Besides the Polish lakes, sequences with laminated sediments were also found in the Cariaco basin, Eifel maars, north-western German lakes, and at Rehwiese in eastern Germany. The Eifel maars, in particular the correlation of the Meerfelder Maar and the Holzmaar, provided an almost continuous chronology over the past 24,000 years. Tephra from the LSE was found in these sequences. The other records were correlated to the CEDC or the Meerfelder Maar record. In general, patterns observed in the Greenland eventstratigraphy were also identified in these records. However, the limits of the climate events were defined on various proxies in the laminated archives such as sediment composition or pollen frequencies. Again, clear offsets were observed between all records (**tab. 71**). In particular, the duration of the periods assumed to be equivalent to the events in the Greenland isotope record varied considerably (**tab. 70**). Changes in the composition of the sediment were usually more similar to the onset and duration of events in the NGRIP isotope record than vegetation data which yielded very inconsistent results. Thus, depending on the analysed proxy, the limits of the events shifted by several decades within a single record (**fig. 31**). The evaluation of a consistent chronology based on these variable proxies is very difficult because observable differences cannot be attributed with certainty to prolonged response times, false correlation, or chronological disturbances such as a hiatus or non-annual deposition of the laminae. Consequently, these records should only be correlated using independent markers such as tephra layers or radiometric dates.

In summary, tuning of climatic records is useful in a coarse-grained chronostratigraphy but it is not advisable in high-resolution approaches due to different response times. Different response times are due to different, occasionally contrasting impacts of main influencing factors, such as temperature and hydrology, and the varying influence of these factors on different proxies. Sequences based on vegetation data suggested that resilience was a strong factor interfering with the construction of a consistent chronostratigraphy.

Nevertheless, the NGRIP isotope template was also supplemented by a tephrochronological dataset (Mortensen et al. 2005). This additional record allowed for a very precise chronological positioning of marker horizons (Turney et al. 2006; Lowe 2011). Tephras are therefore useful correlation points. Some tephras were also identified in the European terrestrial sequences and, thus, allowed for an evaluation of the precision of the different chronologies. However, the Laacher See eruption (LSE) was not unambiguously identified in the NGRIP record, although it forms the most important volcanic marker horizon in Lateglacial Central Europe.

This marker often appeared in laminated sequences of north-western Europe but it was also integrated in the dendrochronologically record. Having positioned the marker horizon of the LSE in the laminated records of Europe and possibly having identified it in the NGRIP tephrochronological record, the dendrochronological record which comprises data for this event can be correlated in this chronostratigraphy.

With the correlation of the dendrochronological data sets using the LSE, the Lateglacial calibration record was automatically reset. In comparison, the proposed position of the dendrochronological calibration data slightly differs from the two most commonly used calibration curves (IntCal09 and CalPal-2007$_{HULU}$). Therefore, a new Lateglacial calibration curve was constructed for the present study (see p. 358-364). The use of this new calibration curve is more appropriate in this project to establish the complete analyses in a consistent chronostratigraphic system of climate and environmental change to which the human changes were related by ^{14}C-dated archaeological records.

Environmental reconstruction

For the environmental reconstruction a variety of datasets, stratigraphies (see Material-Environment, p. 30-48), and dates (see Material-Databases, p. 49-53) were used. In particular, the creation of maps of Lateglacial north-western Europe to visualise the development of the physical geography during the studied time period required a compilation of various data (see p. 253-259). Regression stages of the European ice sheets were taken from the literature as far as possible (Lundqvist/Wohlfarth 2001; Clark et al. 2004; Ivy-Ochs et al. 2008) and interpolated in analogy to the given information for the areas and stages for which these limits are thus far unknown. Furthermore, the rising sea level was selected according to a global dataset (Weaver et al. 2003) and the mid-point of four determined Lateglacial sub-periods (**tab. 47**). For the physical base maps, the NASA shuttle radar topography mission (SRTM) data combined with bathymetric data by the Scripps Institution of Oceanography, University of California San Diego was used (ftp://topex.ucsd.edu/pub/srtm30_plus/; Becker et al. 2009; cf. Sandwell/Smith 2009). Modern disturbances such as open quarry fields or sediment fans of rivers were graphically revised but this data could not be corrected for isostasy or aeolian deposits. Thus, the base maps can only give an approximation of the past landscape. A digital elevation model (DEM) with a sufficient temporal resolution is yet not available for north-western Europe but could be a fruitful project in the future. In the studied area, the impact of isostasy and aeolian deposition was relatively insignificant since the Lateglacial and such details would be lost anyway due to precision of the dataset. Based on these maps, results from various studies about the physical geography were compiled in a short history of the landscape development in north-western Europe (see p. 370-383). In this compilation, restrictions for occupation by plants and mammals as well as for human mobility such as ice sheets, permafrost, or large water bodies were focussed on but more short-term obstructions such as earth-quakes and aeolian deposition were also included.

The cold landscape of the Late Pleniglacial was characterised by braided rivers, occasional permafrost, and irregular aeolian dust deposition. The fronts of the major ice sheets that had been retreating significantly since the LGM were very inconsistent in this period and some glaciers still formed barriers also in the lower mountain ranges such as the Vosges Mountains. Seasonality had presumably a strong effect on this landscape. The transition to the warm landscape of the Lateglacial Interstadial appeared gradually creating a longer interval in which some rivers still flowed in braided systems, whereas others were already settled in meandering river beds. In some areas, permafrost had already completely disappeared and soil horizons started to develop, whereas sporadic permafrost still persisted in some other locations. Although aeolian dispersal in general ceased, irregular loess deposition continued in some areas. These differences formed a very mosaic landscape. Ice sheets retreated rapidly resulting in structural instability provoking earth-quakes and tsunamis in Northern Europe. Moreover, global meltwaters quickly raised the sea-level and first areas in the north were submerged. This period of transition started during the end of the Late Pleniglacial and continued into the early Lateglacial Interstadial. During the GI-1c event, the warm landscape was completely established with mostly meandering river systems and ubiquitous soil development. Probably, a major ice sheet existed only in Scandinavia, whereas the other ice sheets had shrunken to glacier fields or completely disappeared. In Northern Europe further parts of the landscape were submerged but the rise of the sea-level had slowed down. The developments during this temperate period were so sustainable that in the succeeding stadial period, conditions comparable to the transitional period rather than to the Late Pleniglacial reappeared.

Pollen and other vegetation data from the Eifel maars are available for the Holocene, Lateglacial Stadial, and Lateglacial Interstadial as well as for a short period of the Late Pleistocene. For the Paris Basin, a synchronised pollen sequence was established from the end of the Late Pleniglacial to the onset of the Lateglacial Stadial.

This relative sequence was supplemented by ^{14}C dates of which only four dates were considered reliable in a technical audit. This technical audit was one part of an evaluation accomplished for all ^{14}C dates used in the present study; the other part was a contextual audit which was performed before and after calibration (see p. 259-265). Using the previously constructed radiocarbon calibration curve, the four reliable dates of the French synchronised pollen profile were calibrated and the most reliable position was established by correlating the results along the NGRIP oxygen isotope record (see p. 384-388). The profile was stretched and compressed according to these calibration results and, thus, tuned to the NGRIP eventstratigraphy. A comparison of this tuned French sequence and the pollen profile from the Eifel (**fig. 52**) revealed that the French record begins earlier than the Eifel one, that some general differences in the vegetation development exist between the regions, and that changes usually occurred earlier in the French record. The general differences can partially be explained by different local climates with northern France tending to be drier than the Eifel region. The generally earlier response of the French diagram can be due to the correlation along the isotope eventstratigraphy but the clearly earlier beginning of the record might be related to the earlier disappearance of permafrost from this region and the onset of biome development.

At the end of the Late Pleniglacial, the pollen profiles suggest a sparse vegetation cover with wide-spread grasslands (**fig. 53**). The vegetation begins to gradually become denser around the onset of the Lateglacial Interstadial. During the first warm sub-event (GI-1e), arboreal pollen (AP) increases slowly, perhaps influenced by increased volcanic output in this transitional period. The AP increase was mainly due to the expansion of shrub communities, in particular, by juniper, willow, and birch. However, a first important spread of trees possibly appeared in the study area during the second part of GI-1e. This gradual development was stopped abruptly by a rapid expansion of open herbal steppe vegetation. Whether this sudden decrease of AP was related to returning cold conditions during GI-1d cannot be answered with certainty, changes in other factors such as aridity, wind intensity, or wind tracks could also be possible explanations. These factors could have changed after the onset of the severe cold episode of GI-1d. In fact, although the vegetation, in general, becomes denser and, in particular, light pioneer forests establish, the vegetation development is very unsteady with quickly alternating periods of dense and open vegetation until GI-1c_1. During this second half of the Lateglacial Interstadial, the light forest environments established and gradually turned from pioneer to established forest communities. Perhaps, this stabilisation was related to a significantly decreased volcanic sulphate output. Towards the Lateglacial Stadial, the vegetation became more open again but with values comparable to the early Lateglacial Interstadial suggesting that shrub communities and light forests persisted in sheltered locations.

Preservation of pollen seems to begin at the onset of the first transitional phase in the development of the physical geography. Thus, information about the Late Pleniglacial is small in this record and supplementary data has to be collected. This supplement was mainly provided by directly ^{14}C-dated macro-remains as well as macro-remains from archaeological contexts such as charcoal. The latter indicate the availability of wood, usually willow and pine, during the Late Pleniglacial. However, the exact origin of this wood cannot be determined, although the presence of some trees in sheltered areas appears possible. With the onset of the Lateglacial Interstadial, the preservation of datable material as well as the diversity of determined species increased. In general, these species reflected expanding shrub communities, in particular of birch species, comparable to the pollen profiles. During the unstable period in the pollen profiles, willow became important besides the birches. With the stabilisation of forest communities, pine becomes dominant among the macro-remains and continues to be dominant during the Lateglacial Stadial.

Comparable to the macro-remains, the faunal record was mainly reconstructed by directly ^{14}C-dated and determined specimens as well as species found in the archaeological context. Using probability distributions of calibrated ^{14}C dates (**figs 60-61**) to establish population dynamics of commonly hunted species such as horse or reindeer produces results that are no more meaningful than first and last appearance data (see p. 412-432). This ineffectiveness is revealed by a comparison with the presence of the same species in the archaeological and palaeontological record (see **tabs 77-79**). The probable reason is a considerable bias of the datasets by human subsistence strategies, selective preservation, and modern research interests resulting in unbalanced dating strategies. However, with the record of directly ^{14}C-dated species supplemented by well contextualised determinations of species from reliably dated records, a well funded chronology of presence and absence of some selected species can be established for several regions from the LGM to the onset of the Holocene (**fig. 63**).

This compilation reveals that after the LGM the faunal record still remains small until the end of GS-2b and the main Heinrich 1 event (cf. Stanford et al. 2011b). After the main phase, the fauna reflects an open vegetation community with several larger mammals such as reindeer or horse that are known in modern periods to have occasionally formed large herds. These herds were supplemented by a rich faunal community which contains grass steppe inhabitants such steppe bison but mostly species that are found in modern arctic regions such as arctic hare, arctic fox, and occasionally musk ox. A northward shift of this faunal community began at the end of the Late Pleniglacial. In the studied regions, typical inhabitants of arctic tundra such as musk ox disappeared and other species associated with more temperate environments appeared such as elk, red deer, and wild boar. A regional difference is the absence of wild boar in the western upland zone including the Central Rhineland and the absence of elk in northern France. Possibly, this absence was related to the lower moisture and higher vegetation cover in the Northern French floodplains. However, horses became the dominant species in the assemblages but reindeer still occurred sporadically in northern France. Reindeer disappeared from the study area with the end of the cold sub-event of GI-1d. The importance of horse decreased significantly at the same time but horse was still present in the areas until the Holocene. After GI-1d, species indicating temperate forests such as roe deer appeared. In the Central Rhineland, these were supplemented by wetland species such as beaver. In northern France, aurochs also indicated forest environments. Wild boar was attested only for the end of the Lateglacial Interstadial in the Central Rhineland when the importance of pine also increased in this region. The temperate faunal communities were not replaced completely during the Lateglacial Stadial. In areas adjacent to the North European Plain, more arctic species such as arctic fox and reindeer reappeared but in northern France aurochs remained present in addition to horse. During the Holocene, temperate species expanded rapidly into the northern regions of the study area. This development indicated that in the faunal communities, likewise the physical geography and the vegetation record, a transitional period bridged the period of the Late Magdalenian and the period of the FMG. The beginning of the transitional phase appeared gradual but the end was relatively rapid and, therefore, the latter appeared as more fundamental.

Behavioural patterns based on the archaeological record

The archaeological record (see Material-Archaeology, p. 75-244) examined in the present study is based on well known sites from the Central Rhineland, the Paris Basin and the Somme region, and the uplands between these areas. These sites were chosen because of the comparable archaeological record which was previously interpreted as consolidated information system (the extended Nebra group, Floss/Terberger 2002). In the material chapters, the published information about the sites and their archaeological material were summarised. This information was compiled per sub-area in eleven model tables (**tabs 10-44**). The internal chronology as well as the general chronostratigraphic position of each site was evaluated based on available chronological indicators. In particular, the ^{14}C dates were examined along the same criteria as the environmental database and, in addition, the relation of the radiometric result to the dated archaeological material was considered (see p. 265-269; cf. Dean 1978). Compared within the sub-areas, periods of transition were established for the Central Rhineland (**fig. 65**) and northern France (**fig. 69**). In the Central Rhineland, this transitional period was relatively long due to the relatively sparse archaeological record from this time. In the French record, three periods were identified in which different archaeological units overlap. These periods imply a continuous but uneven process of change. In a next step, a succession of sites from all studied areas was established (**fig. 70**) and suggested that the long transitional period from the Central Rhineland encompassed the two first transitions of northern France. Moreover, the succession of the archaeological sites suggests that during the mid-Lateglacial Interstadial two different varieties existed concomitantly in northern France and the Central Rhineland. After the third transition, a variety more comparable to the one in Central Rhineland was also established in northern France. Thus, according to the archaeological units, only one transition can be identified in the Central Rhineland in contrast to three transitions in France. This observation suggests a more conservative behaviour in the Central Rhineland than in northern France.

Besides the variable tempo, this different perception also arises from the examined part of the archaeological record. To systematise changes in the archaeological record according to their effect, this project uses a refined version of a hierarchical system (**tab. 62**) introduced previously for the study of human material culture and population history (see p. 289-291; Foley/Lahr 1997; Gamble et al. 2005). Archaeological material systematised in this hierarchy reflects an increasing number of individuals which conformed to the same behavioural pattern to create the archaeological observation. For example, a single individual made a retouch on an artefact on a molecular scale, a family group organised the space of a site on a micro-scale, one or several groups formed a settlement system on the meso-scale, and generations formed a tradition of using space on a macro-scale. Variations on the individual scale are probable to occur constantly due to human imperfection in reproducing behaviours and behavioural expressions (Eerkens 2000; Eerkens/Lipo 2005). Correction by others (Hamilton/Buchanan 2009) leads to a decrease of unintentional variation on higher hierarchical levels, whereas the number of people who must agree and/or be able to conform to new behavioural patterns increases. Thus, the higher in this hierarchical system a change is observed, the more effective was it for the Lateglacial society. However, some changes in the archaeological record were probably interrelated because the different parts belonged to the same complex behavioural recipe (cf. Mesoudi/O'Brien 2008b). For example, the production of lithic points at sites attributed to the MfCM possibly represented a complex behavioural recipe: To produce short but straight blades for the transformation into points, the knapping instrument was changed to a soft hammerstone and this change also led to different reduction strategies that subsequently permitted a different raw material economy (Valentin 1995; Valentin 2000; Valentin/Julien/Bodu 2002; Valentin 2008a; Valentin 2008b). A chronological vicinity of changes in such interrelated parts of the record should not be considered as multiple but a single process of decision making that resulted in the fully new complete behavioural recipe.

To establish the progress of variations more precisely and allow for an evaluation of the observed variations, several parts of the archaeological record were analysed on several levels from the molecular scale such as the measures of lithic projectiles to the meso-scale, for example, the long distance connections that are expressed by the acquisition of resources. A particular focus was set on exploitation strategies (see p. 485-509 and p. 534-548) and spatial organisation (see p. 548-559) as behaviours that are interdependent with the natural environment and that are therefore particularly sensitive towards alterations in this environment. The acquisition of resources, in particular, lithic raw materials is often difficult to establish (see p. 569 f.) because the exact sources are not known or, in the case of secondary deposits such as river gravels, spread over a wide area. However, a detailed itemization of raw materials found at the analysed sites and the nearest possible origin of these materials (**tabs 12. 25. 36**) confirmed the previously observed disappearance of very long distance transports in the study areas and the increasing use of local resources (cf. Floss 1994; Baales 2006b; Street et al. 2006). Increasing knowledge of the landscape and, in particular, of source qualities seems no probable explanation for this variation because the Late Magdalenian already knew and exploited high-quality local resources. A connection with technical innovations permitting a more flexible use of the lithic raw materials appears a more likely explanation. In addition, the comparison of the distances indicated a wider local zone in northern France than in the Central Rhineland. Moreover, this comparison also revealed a tendency of exploiting the immediate local surrounding and again a more distant regional surrounding. Intermediate distances were hardly identified. This gap in the raw material acquisition distances could be compensated by the diffuse distribution of some raw materials. However, if this gap proved valid in a future, more precise source location survey this behaviour could implicate specific site movement behaviour (**fig. 94**) that, perhaps, was performed to allow the exploited ecology to recover. Furthermore, a comparison with neighbouring areas of the Central Rhineland suggested that the directions of a flow of raw materials along the Rhine might have changed during the transition from the Late Pleniglacial to the Lateglacial Interstadial. A changed direction of this flow could reflect variations in the seasonality and routes of the settlement system in this extended region.

To establish changes in exploitation strategies, numerous parameters were produced for the lithic (see p. 270-272) and faunal assemblages (see p. 282-285) of the analysed sites. In particular, the lithic inventory was studied with some detail in regard to the applied exploitation as well as the observed diversity assuming that the settlement type and the spatial organisation affected the lithic raw material economy at the sites (see p. 286 f.). The resulting parameters were directly compared in a temporal succession per site and per attributed archaeological unit (**fig. 74A**).

Firstly, the lithic assemblages were compared by their numerical size identifying the assemblages of FMG sites as tending to be small and MfCM assemblages as particularly numerous (**fig. 73**). This observation gives the impression of a wasteful handling of resources at the latter sites. To further test this impression further criteria indicating a wasteful exploitation were considered. These criteria are the density of lithic material on a site, the number of cores and the portion this group makes up of the complete assemblage, the relation of cores to the debris material of the site termed the exploitation index, and the relation of cores to formally retouched artefacts termed function index. The density was strongly biased by the spatial organisation of the sites and the limits of the archaeological excavations resulting in some extreme outliers. Nevertheless, a clear difference was found between the generally dense Late Magdalenian and MfCM sites on the one hand and the ephemeral Early Azilian and FMG sites on the other hand (**fig. 74B**). In the comparison of the cores, increasing proportions of cores were found in the chronologically younger assemblages, whereas the numbers of cores remained, in general, comparable (**fig. 75**). However, several MfCM and some FMG assemblages yielded clearly higher numbers of cores than the other sites. Usually, the site formation could explain the high numbers at FMG sites with obviously repetitive visits creating higher numbers of cores for the complete site. If these numbers were considered per concentration they fell in the normal range. Bad Breisig formed the only exception. The exploitation index showed that the number of knapped material per core generally decreased from the Late Magdalenian over the Early Azilian to the FMG (**fig. 76**). However, in the Late Magdalenian, two types of assemblages were found which appeared to relate to different types of use of these sites. In the MfCM assemblages, this index varied considerably with the upper horizon of Le Grand Canton producing particularly low values. The function index showed again a difference between the sites of the Late Magdalenian with the large sites of Gönnersdorf and Andernach being clearly dominated by retouched artefacts and smaller sites and possible hunting camps yielding a smaller dominance of retouched artefacts (**fig. 77b**). The values of the Early Azilian assemblages scattered between the two groups of the Late Magdalenian, whereas the values of the MfCM assemblages fell to the lower Late Magdalenian group and even below this one. The FMG assemblages had a comparable range indicating the decreasing numerical importance of formally retouched artefacts and the increasing proportion of the blank production process. For the majority of MfCM sites, the hypothesis of a particularly wasteful handling of raw material could be qualified due to the excavated areas and the high values were explained by an intense blank production performed at these sites. By contrast, for Gönnersdorf III, the upper level of Le Grand Canton, and Bad Breisig the criteria suggested a more wasteful handling of raw materials revealing this behaviour as a diachronic phenomenon. However, in these assemblages small-sized raw material nodules that were available in large numbers in the immediate vicinity were used. The number of these small-sized pieces seemed to have been a substitute for fewer but larger raw material nodules. This trend in connection with the less restrictive acquisition of raw materials resulting also in the use of smaller-sized material during the time of the FMG could explain the impression of an increasingly wasteful exploitation strategy in the Lateglacial. Nevertheless, a greater wastefulness could be rejected as an explanation of large and very large assemblages. Intense lithic exploitation and a frequent use of sites appear better explanations of large and very large assemblages in this period. The comparison per archaeological unit further demonstrated that in the Late Magdalenian sites seemed to be used for special purposes and, therefore, produced sometimes very different values. In contrast, MfCM, Early Azilian, and FMG sites appeared more similar. The latter sites seemed as a combination of the Late Magdalenian site types, whereas the MfCM and the Early Azilian sites appeared to reflect a single, opposing site type. This finding raises the question whether these two archaeological units represented two complementary units.

Diversity of lithic assemblages was considered as indicator for time in various senses: as an indicator for the occupation duration of the site (Löhr 1979; Richter 1990) as well as the position in a typo-technological chronology. The latter further makes an evaluation of the diversity between quasi-contemporary assemblages possible and, thus, allows considerations about the stability of socially given norms. Therefore, diversity of lithic assemblages is important in the study of a transition process. The composition of the complete lithic inventory that had already served in the discussion of the exploitation, the composition of the formally retouched artefacts, and, in particular, of the LMP was therefore analysed (see p. 272-282).

The proportion of the formally retouched artefacts showed a significant variability in Late Magdalenian assemblages (**fig. 77a**). In general, this proportion decreased during the Lateglacial with the disappearance of inventories that were strongly dominated by formally retouched artefacts. The latter becomes apparent when directly compared to the numbers and proportions of cores (**fig. 84**). A more detailed comparison of the structure of the formally retouched artefacts (**tab. 83**) indicated a decreasing conformism to classical tool types. In addition, this comparison showed that the LMP are the most basic group of formally retouched artefacts followed by burins. These two groups were usually found within Lateglacial inventories of formally retouched artefacts. The proportion of the supposed elements of hunting equipment were variable but in general in a similar range but at Late Magdalenian sites smaller proportions were occasionally found, whereas the FMG assemblages sometimes yielded higher proportions (**fig. 80A**). The MfCM and the Early Azilian sites produced generally lower values of LMP. Perhaps, this observation was due to the general absence of backed bladelets in these assemblages. In late Magdalenian sites, intentional breakage of backed bladelets was recorded already resulting in higher numbers of LMP than the use of points. In addition, these bladelets were probably used in higher numbers per projectile, whereas the large lithic points from the MfCM and Early Azilian sites were considered to be used as single lithic implement. Thus, a considerably higher number of LMP was produced for the same number of projectiles when backed bladelets were used. Perhaps, this explained the higher proportions at FMG and some Late Magdalenian sites. To evaluate a suggestion that the use of lithic points and a decrease of burins in Lateglacial assemblages reflected a

lower availability of suitable organic sources such as antler for the production of hunting equipment (Lang 1998), the number of points, burins, end-scrapers, and borers were compared. In the context of reindeer gradually disappearing from northern France during the faunal transition period, this suggestion seemed to offer a possible explanation for changes in the archaeological record. However, based on the present results (**figs 80B-81**), this suggestion cannot be confirmed, although it can also not be completely rejected. In fact, the detailed comparison indicated a considerable variety between the assemblages, between the archaeological units as well as within the single archaeological units. This variation raised some questions: Were borers no longer of use or was the function performed with another artefact? Was the function of specific tool types, perhaps, varied within the Lateglacial? A compilation of the existing traceological results and further, diachronic analyses of numerous pieces from different inventories would be desirable in the future to provide further insights in this complex subject. In the context of possible changes in the tasks performed with a specific formally retouched artefact group and the previously indicated differentiation in the use of space in this period, the question must be asked whether the suggested use of the Simpson diversity index to evaluate the duration of Magdalenian occupations (Richter 1990) can be applied likewise for other Lateglacial archaeological units (cf. Gelhausen 2011b). The results for the Late Magdalenian and the other archaeological units are generally similar but the variety increases in these other units (**fig. 82**), in particular, Early Azilian and FMG values cover a greater range and produced more often specialisations in single artefact groups. These specialisations have to be considered in the spatial organisation of sites and the excavation limits. Therefore, the use of this index as indicator for occupation duration must be supplemented by a spatial analysis of the concentration and its position in the site context as well as in the settlement system.
The diversity in the LMP was established by shape (**tab. 85**) and by dimension (**fig. 83**) to document changes probably associated with the hunting equipment that is considered as most sensitive to changes in the natural environment. Furthermore, a greater variation in this record can also be understood as an experimentation phase which is of some interest studying behavioural change. The lowest variability of shapes was found in the Late Magdalenian and the greatest variability was found in the mid-Lateglacial Interstadial from approximately GI-1d to mid-GI-1c but the variability of shapes remained relatively high afterwards. This period equates the end of the transition period in the Central Rhineland and towards the end of this transition also the highest variability in the dimension of the LMP appears suggesting that in some assemblages two or three size classes of LMP existed which were either used in different tasks or in different weapon systems. Besides this indication of variability, the variances of the LMP also revealed important standard measures. For example, width appeared to be a very standardised value in Late Magdalenian backed bladelets, whereas length was the standardised parameter of *Federmesser*. Probably, these standards were closely related to the hafting of the lithic implements into the projectile shaft.
Some sites provided in addition to the lithic assemblage also a faunal record. Although preservation conditions varied, the better preserved FMG assemblages such as Kettig showed that the production and use of organic tools had significantly decreased in comparison to the Late Magdalenian. Possibly, the faunal material was substituted by wood that was not preserved. The choice of prey animals generally follows the appearance and disappearance of the animals in the studied area. However, in the Central Rhineland the transition in the faunal assemblages was shorter indicating the more conservative behaviour. The number of different species is bisected for the Late Magdalenian again according to the different site types, whereas the FMG yielded a small range of numbers (**tab. 86**). The preservation of the bone material suggested that a change in the disposal of faunal remains occurred with material on FMG sites being usually burnt. In Late Magdalenian sites, very small pieces appeared that were considered in an intense exploitation of animal resources comparable to ethnographic examples of a »nothing is wasted« strategy (Pasda/Odgaard 2011).

This cooking of very small faunal fragments allowed a disposal near the site without attracting predators and vermin. Perhaps, for the same hygienic reasons not so intensely exploited material had to be burnt at FMG sites. This difference implies that at FMG sites a sufficient surplus existed that made discard of potential nutrition possible. The exploitation of smaller mammals such as hare but also carnivores was comparably considered as buffering mechanism in insecure environments (Charles 1997b; Stiner et al. 1999; Munro 2003; Zeder 2012). The proportion of these smaller mammals decreased over time (fig. 86) sustaining the impression that the intensity of exploitation of alimentary resources decreased from the Late Magdalenian to the FMG. In particular, values were very low at MfCM sites. To what degree selective preservation at these sites was a major agent in the creation of this pattern cannot be fully evaluated. However, this selective preservation had possibly some influence on the specialisation index of the faunal assemblages (fig. 85) resulting in some hyper-specialised assemblages. The Late Magdalenian faunal assemblages displayed a bipartition that reflected the often before observed different site types. This differentiation becomes inconsistent during the second transition in northern France. The FMG faunal assemblages appear rather diverse.

Thus, a change in the spatial behaviour during the Lateglacial was identifiable by the archaeological record. In particular, the diversity of the formally retouched inventories in comparison to the number of formally retouched artefacts (fig. 89b) and the diversity of the faunal assemblage compared to the minimal number of individuals showed very different functions of the sites (fig. 89a). The position in these systems shows the short-lived opportunistic character of most assemblages. These comparisons also revealed some Late Magdalenian, MfCM, and FMG assemblages as exceptional outliers and, again, the almost opposite character of MfCM and Early Azilian assemblages becomes obvious. This opposition becomes further apparent when the sites were displayed in a direct comparison of the diversity of formally retouched artefacts and faunal assemblages (fig. 90). According to a predefined connection of this display to the settlement system (tab. 59), the MfCM sites would reflect long-term hunting camps or short-term base camps, whereas the Early Azilian sites would represent provisioned special task camps or opportunistic episodes. The Late Magdalenian sites form again two groups between potential base or agglomeration camps and hunting-camps, whereas the FMG sites encompassed the Late Magdalenian sites and ranged between the MfCM and the Early Azilian sites. Providing additionally information about settlement structures in this comparison (fig. 91) shows that pavement and pits were only found in large base camp or agglomeration sites. Hearths identified by stone setting and those identified by stone packing seemed to occur, in general, on different types of sites. Alteration of the sediment tended to be more common on site types comparable to those with the stone setting. Putting the seasonal indication for these sites on this display (fig. 92), a distinctive trend can be observed with the MfCM being more frequently used during the light season and Early Azilian sites tending to be used during the dark season. This dichotomy provides further arguments for different, possibly complementary, functions of these archaeological units. Moreover, the connection of dark season and almost all year round use of base camps and hunting camps being rather in the light season during the Late Magdalenian is disintegrated at FMG assemblages that show nor clear relation between site type and seasonality. Establishing a hypothetical model of site type distribution in relation to the diversity of the formally retouched artefacts and the faunal assemblages as well as in relation to the faunal environment (fig. 93), the dichotomy of the MfCM and the Early Azilian sites matches well to the differences of hunting and base camps in areas with non-migratory species. Besides the different functions, the spatial layout of frequently used sites varied considerably with a tell-like use during the Late Magdalenian and occasionally the Early Azilian, a peripheral shifting at MfCM sites, to a suburban style with clearly separated but almost identical concentrations at FMG sites.

Chronology of changes in the Lateglacial record

The compilation of the various changes reveals several points:
Vegetation and fauna did not react directly to climate changes because further factors such as the soil formation also played an important role in these developments. Human behaviour was similar and reacted to a variety of external stimuli among which climate was not a directly effective and/or important factor; environmental developments which resulted in resource variation were certainly of a greater importance.
The Lateglacial hunter-gatherers gradually changed their behavioural patterns which can be regarded as an evolutionary process (**fig. 95**). When less people were involved in the decision-making process variations occurred more readily and, thus, on lower analytical scales variation appeared more frequently. Sometimes observed variations were interrelated and an accumulation of changes in interrelated parameters must be considered as a change in a complex behavioural recipe. However, in a relatively short period (*c.* 250 years) in the mid-Lateglacial Interstadial several changes in many analysed parameters, also several unrelated ones, and at different analytical scales were observed. This short-term process can be considered as a revolution or step-wise change (**fig. 96**). After this rapid episode of change, FMG sites were established in the Central Rhineland. Consequently, the transformation from the Late Magdalenian to the FMG can best be described as a phase transition-like process with a gradual beginning and a sudden, almost exponential rise if a critical threshold is passed. The starting point of this accelerated development can be seen in the cold phase of GI-1d and the subsequent establishment of light forests environments. This major change in the vegetation and the faunal record coincided with the onset of the accumulated changes in the archaeological records. In northern France, another faciès was first established after this rapid rise. The number of characteristics that this faciès shared with the FMG of the Central Rhineland was relatively high and, perhaps, the differences can be attributed to a specific environmental adaptation.

EXPLAINING REORGANISATION OF SOCIAL SYSTEMS IN THE CONTEXT OF CLIMATIC AND ENVIRONMENTAL CHANGES

In a study of changes in behavioural patterns, precision in chronology, terminology, and the research focus have to be endeavoured to provide and fill a common research frame. This endeavour was attempted in this analysis for climatic, environmental, and archaeological data from the Weichselian Lateglacial. The records and the combination of these records in the same frame delivered the above presented results.
An interpretation of these results must consider that humans form dynamic, complex, and adaptive social networks as survival strategy. Further survival strategies shape the behavioural standards of these networks. These specific behavioural standards were contextualised in their natural and social surrounding and adapted to changes occurring in these environments. Consequently, behavioural variation is also directed by the developmental history of these standards.
Contextualising the Lateglacial record in the recolonisation process of north-western Europe after the LGM, the still relatively low population density during the Late Magdalenian in combination with a persisting climatic and environmental instability required large networks to secure the survival of the single groups as well as of the metapopulation (cf. Stein Mandryk 1993; Hanski 1998). To remain connected across these wide areas, a very conservative lifestyle had to be sustained. This sustenance of security networks also functioned as distributor of information. The fast exchange of information also worked as a buffer-

ing mechanism against the insecure surroundings. In particular, modification in subsistence and hunting strategies were communicated quickly to provide nutritional security. Smaller variations of the hunting equipment appeared regularly and useful innovations were spread rapidly during this period. However, these high-precision composite weapons had to be geared to the needs of the hunters, the characteristics of the prey, and the availability of the single components. Thus, they formed a complex behavioural recipe (cf. Mesoudi / O'Brien 2008b) in which acquisition, techniques of the production and use, and the application of the instrument had to be balanced. Variation in one of these parts could have resulted in changes in other parts. Subsistence strategies were, in general, modified towards a generalist approach (cf. Gaudzinski / Street 2003) and first steps on a broad spectrum revolution were also detectable in the incorporation of smaller mammals (see p. 543-546; cf. Munro 2003; Zeder 2012), birds (cf. Street / Turner 2013), fish, and, possibly, marine resources in the diet (cf. Pétillon 2008a; Langley / Street 2013). Moreover, the faunal material was intensely exploited similar to a »nothing is wasted« strategy known from ethnographic examples (Pasda / Odgaard 2011). Mobility patterns in this environment of limited resources and important social contacts across longer distances had to be strictly organised. To guarantee the functioning of this complete system, individuals had to be trained (cf. Pigeot 1990) and regularly monitored to prevent variation to be accumulated (Eerkens / Lipo 2005; Hamilton / Buchanan 2009) resulting in a potential non-functioning that could have fatal consequence for the individual as well as a complete group. Thus, conservative behaviours compensated for an enormous need for security (Maslow 1943) in these human groups and resulted in a remarkable resilience. This resilience of the Late Magdalenian was sustained by the ability to adapt to unstable environments by small-scale variations in the behavioural patterns (cf. Rowley-Conwy / Zvelebil 1989; Jochim 1991; Walker et al. 2006). Furthermore, this resilience formed the developmental history that directed the following period of change.

During the transition towards the Lateglacial Interstadial and the gradual changes in the climatic, physical, and environmental conditions, hunter-gatherer groups in north-western Europe remained in this Magdalenian modus and reacted to these changes with minor modification of their behaviour. The partial coexistence of old, often migratory and new, often non-migratory prey animals, the increasing availability of resources such as wood along with antler, and the temperate climatic conditions with milder winters formed a favourable and prosperous landscape for highly adapted hunter-gatherers. In this surrounding, sufficient surplus could be created without intense exploitation and non-conformity was not necessarily punished by harsh climatic and environmental conditions. With the continuity of this more favourable context, safeguarding mechanisms such as the intense faunal exploitation were gradually neglected, abandoned, and finally forgotten. In this period, behaviours became more flexible and did not sustain connectivity.

The return of harsher climatic conditions combined with the return of aeolian sediment transport during the cold sub-event GI-1d resulted in nutritional stress that could no longer be compensated by buffering mechanisms such as increased exploitation intensity or long-distance security networks. This seems to have resulted in a decreasing population and the collapse of the Magdalenian. Thus, uncontrolled variation in combination with neglect of safeguarding strategies led finally to the collapse of Magdalenian lifestyles.

The collapse of the Magdalenian was the beginning of the Azilian. With the return of temperate but unstable environments, previous behavioural patterns were rapidly replaced. Within 250 years, a FMG lifestyle was established in the Central Rhineland and another Azilian faciès in northern France. Although some relevant changes in the behavioural repertoire were observed, the Azilian was clearly descended from the transitional phase when uncontrolled variation had produced behaviours adapted to temperate environments with denser vegetation. In particular, Early Azilian assemblages indicate these variations in lithic techniques and prey choice but the spatial behaviour detected at these sites clearly places this archaeological unit among the Magdalenian groups.

An explanation for this sudden replacement after the long period of gradual variation can be found in the formation of beneficial alliances to answer, besides insecure environments, also to social competition that led to the development of cooperative behaviour (Byrne 1996; Charlton 1997; Dunbar 1998). The highly adaptable but also highly conformist social system of the Late Magdalenian was a beneficial alliance and formed the last almost pan-European hunter-gatherer entity which shared a common set of traditions from Portugal in the west to eastern Poland and from the Mediterranean to the limits of the North European Plain. However, alliances can break up rapidly when a new alliance offers to be more convenient or competition promises to be more beneficial than allying (cf. Han/Pereira/Santos 2012). The emergence of new alliances has to be supported by a substantial part of the community members to be beneficial and, consequently, new rules for socially selected behaviour often occur in a phase transition-like manner (cf. Gavrilets/Duenez-Guzman/Vose 2008; Abel/Cumming/Anderies 2006). This manner was observed in the archaeological record from Lateglacial north-western Europe.

Furthermore, in an analysis about the impact of volcanic eruptions on past societies, minor impacts were shown to have had major effects on societies which were already destabilised, whereas major impacts had only little or no impact on resilient communities (Grattan 2006). This result is comparable to findings of this study.

In conclusion, climate change is no disaster for well connected societies that are flexible enough to adapted to changing conditions. However, if social agreements are already disintegrating the impact of minor changes can have major consequences. Thus, also resilient societies facing a climate change must consider long-term results of their small-scale adaptations and strengthen social cohesion to prevent a later failure due to minor external triggers.