The repeated replacement model – Rapid climate change and population dynamics in Late Pleistocene Europe

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Abstract

The disappearance of Neanderthals from the Palaeolithic record in Europe remains an enigma, even after more than 150 years of research. This paper identifies Rapid Climate Change during the Glacial period as a major factor that influences a variety of cultural, economic and demographic processes during the European Palaeolithic. In particular, and in agreement with many previous authors, climatic deterioration is put forward to explain multiple population breakdown during the European Palaeolithic, as well as to explain corresponding major cultural changes. Taking the archaeological record of the Iberian Peninsula as a case study, the Repeated Replacement Model (RRM) is proposed to explain population turnover in Europe during the most extreme climatic phases of the Glacial, the occurrence of North Atlantic Heinrich Events (HE). The strong aridity of the Mediterranean during HEs appears to have limited settlement refugia to such an extreme extent that communication networks and cultural traditions broke down and were subsequently reorganized under different socio-cultural conditions. The transition from the Middle Palaeolithic to the Aurignacian during HE 4 is one of these cultural turnover periods, which saw the final (macro-scale) extinction of Neanderthals and their widespread replacement by Anatomically Modern Humans. More specifically, and recognizable by comparisons with other climatically extreme Glacial periods (i.e. HE 3, and HE 2), the model excludes the survival of geographically wider (supra-regional) human networks, but it does allow for (micro-scale) survival of scattered groups. From this model, some kind of admixture between Neanderthals and incoming groups of modern humans would indeed have been possible on a small scale. If this climatic scenario turns out to be correct, the most spectacular thing about Neanderthal disappearance might actually lie in the seemingly unspectacular nature of the processes involved.

1. Introduction

Looking back on more than 150 years of research on Neanderthals means to look back on a number of highly controversial debates, especially within the last two decades. A large number of hypotheses and speculations concerning the transition from Neanderthals to anatomically modern humans as well as the second phenomena of technological transition from Middle to Upper Palaeolithic techno-complexes have been put forward by expert members of the various scientific disciplines. Despite this plethora of opinions, the high variability of Late Pleistocene climatic change in Europe is now widely acknowledged. This new palaeoclimatological understanding provides an important stimulus for further archaeological discussions. Researchers must now seriously allow for the possibility that the observed climatic and environmental changes were also influential in terms of cultural variability. In support of climate forcing as major factor for cultural change, see (e.g.) van Andel and Davies (2003), d’Errico and Sanchez-Góñi (2003), Mellars (2006), Shea (2008), Finlayson and Carrión (2007), and Sepulchre et al. (2007). There are alternative proposals, which place less emphasis on the climatic background for cultural change in the Palaeolithic (e.g. Tzedakis et al., 2007; Roebroeks, 2008; Banks et al. 2008a).

Talking about Neanderthals means to talk about humans living at the very periphery of the Pleistocene human world. These humans represent pioneering populations living on Mediterranean shores, just as at high Northern latitudes. In consequence — and keeping in mind the increasing number of high-resolution climatic records that demonstrate the extreme rapidity and amplitude of past climatic changes — it must now be recognized that the Late Pleistocene in Europe was a period during which human populations repeatedly experienced significant environmental switches, which occurred rapidly on decadal time scales and in...
many different geo-climatic regions (Clement and Peterson, 2008; van Andel et al., 2003). During the Late Pleistocene, considerable parts of Europe must have represented risky environments for humans. Assumining this climatic and environmental variability had major implications for Neanderthals, as well as for modern humans. This paper combines environmental data with chronological data from archaeological sites in Iberia to develop a model for cultural change in Late Pleistocene Europe.

2. Models for climate change

A brief look at Greenland climate curves between 50 ka and 20 ka calBP displays the high climatic variability in Europe during the Glacial period (Fig. 1: Upper). The Dansgaard/Oeschger cycles of sudden climatic amelioration (Greenland Interstadials: GIS) and subsequent coolings (Greenland Stadials: GS) are well recorded in North Atlantic air temperatures ($^{18}O$: Grootes et al., 1993) as well as in the GISP2 glaciochemical record (e.g. nss [K$^+$]: Mayewski et al., 1997). Previous research on the European and Near Eastern Palaeolithic has placed strong emphasis on chronological applications of the stable oxygen isotope ($^{18}O$) records from Greenland ice-cores. The Greenland $^{18}O$-record has indeed been helpful, e.g. in the initial construction of an extended Glacial $^{14}C$-age calibration curve (Jöris and Weninger, 1998), but its direct archaeological applications are to some large extent restricted to the North Atlantic. Indeed, for archaeological applications the Greenland $^{18}O$-record has certain limitations. Perhaps most notably, in the $^{18}O$-record there is no evidence for the existence of the Little Ice Age (ca. 1600–1929 AD) but which shows up strongly in the GISP2 glaciochemical record (Mayewski et al., 2004). Although presently not used by the archaeological community, the GISP2 chemical ion records ([Ca$^{2+}$, Mg$^{2+}$, Na$^+$, K$^+$, Cl$^-$]) appear to have an equally wide applicability, and also some complementary use in archaeological applications, along with the $^{13}C$-record. Significantly, the GISP2 glaciochemical record demonstrates the high variability of Northern Hemisphere atmospheric circulation patterns during the last 60 ky. Further, and also of considerable interest for archaeological research, is the recent discovery (Rohling et al., 2002) that the severe coolings observed in eastern Mediterranean sea-surface temperatures appear to be related to a quasi-periodic expansion and intensification of the Siberian High. These severe coolings (here termed ‘Rapid Climate Change’, RCC) can be seen to run systematically through the Last Glacial into the Holocene and up to modern times. The occurrence of RCC periods are presently best-identified in the GISP2 [K$^+$] record, but also show up in other high-resolution records (e.g. $^{13}C$, SufuralCave, NW-Anatolia: Fleitmann et al., 2009). In the present paper, in search of the expected extreme impact of Heinrich Events (HE), the GISP2-[K$^+$] record is therefore included. To achieve better time-scale compatibility with U/Th-Hulu-based calibrated $^{14}C$-ages cf. below, we have transferred the Greenland GISP2-[K$^+$] record to the U/Th-Hulu time-scale.

Together (Fig. 1), these records demonstrate a long sequence of changes in the strength of the North Atlantic Ocean circulation system, as well as in Northern Hemisphere atmospheric circulation patterns during the Glacial. Altogether, at least 12 major climate cycles are recorded in Greenland ice-cores between 50 ka and 20 ka calBP, including the Late Glacial maximum (LGM). However, similar cycles (e.g. Fig. 1, Lower) show up in marine cores taken from the Alboran Sea, (e.g. Moreno et al., 2005; Jiménez-Espejo et al., 2007; Fletcher and Sánchez Goñi, 2008) as well as the Iberian margin (Roucoux et al., 2005; Naughton et al., 2007, 2009; Salgueiro et al., 2010). These records provide important information as to corresponding changes of neighbouring terrestrial environments. It is a major task for palaeoclimatologists and environmental researchers to accurately synchronise the records from the different geographic realms (ice-core, atmosphere, marine sourced) and to transfer their information contents to the much less-well documented terrestrial regimes. Today, in archaeological research, it must be considered that such rapid and intensive climatic changes had an important impact on geographic frontiers.

3. Human expansion during the Glacial

As shown in Fig. 2, the northern limit of human expansion in Europe prior to the Gravettian (i.e. before 30 ka calBP) is located around 53°–55° N (van Andel et al., 2003; Roebroeks, 2008). In regions further to the east, humans might have reached at that time even higher latitudes (Pavlov et al., 2004). This expectation, that human frontiers in Europe during the Late Pleistocene were continually on the move, is supported by several investigations (Weninger and Orschiedt, 2000; Bocquet-Appel and Demars, 2000; Bocquet-Appel et al., 2005; Gamble, 1993; Housley et al., 1997; Gamble et al., 2004). In the present paper, to achieve more detailed insight into these pulsations, selected radiocarbon and (adapted) environmental data from the Stage Three Project (van Andel and Davies, 2003), which is aimed at simulating the human frontier for selected extreme climatic scenarios (Barron and Pollard, 2003), were used.

As a main simulation component, the modeling studies provided by the Stage Three Project are based on the isolethe for the geographic distribution of annual/daily average snow cover. Davies and Gollop (2003, 143) proposed, prior to 30 ka calBP, a preference of humans to occupy regions with snow cover below 60 days per year and an average tolerance up to 180 days a year. However, as shown in Fig. 2, such minimum-maximum simulations document strong geographic shifts of the isolines and, in consequence, it is expected that in the transitions from Interstadials to Stadials the human frontiers must have displayed some pronounced oscillating effect. The distribution of snow cover isolines provides evidence...
that a number of regions in Europe, and most notably the Northern Mediterranean, Southwest France and the circum Black Sea regions, may all have been used as possible refuge areas for human populations. Similar configurations have been described for Western Europe by Boquet-Appel and Demars (2000).

According to such modeling approaches, hunter gather populations in Europe outside of these refuge areas would have had two possibilities to react to extreme climatic changes: bear up or take flight. Gamble (1993) developed a three-phase model to describe corresponding reaction patterns of hunter-gatherers towards climate forcing. His model starts with a compaction ("downturn") phase followed by a refuge phase and a subsequent expansion ("upturn") phase. This model was further refined by separating the upturn phase into a pioneering and residential phase (Housley et al., 1997). It was then used to explain population variability during cold events around the LGM and GS 2 in Europe (Gamble et al., 2004, 247). Similar to Gamble (1993) and Housley et al. (1997), the authors believe that climate forcing indeed had tremendous impact both on the organization of social networks and on population density. Recently, Hulbin and Roebroeks (2009) argued that the periodical abandonment of some areas in the northern environments of Neanderthals supports a model of local extinction rather than a habitat tracking model. From this point of view, both models can be applied in parallel to the differentiation of population events. Both provide useful descriptions of population dynamics during the entire European Late Pleistocene.

To further understand the relation between population dynamics and climatic variations, on this broader temporal and geographic level, a four steps cascade model is proposed, based on the adaptive cycle representation of societal changes (Fig. 3). Hence, although strongly based on previous considerations, the cascade model goes a step further to allow for extreme climatic variability, and especially for the increasingly high temporal resolution of underlying climate records, as are now firmly established for the Late Pleistocene in Europe (Fig. 4).

The adaptive cycle model was generated from observations in ecosystems (Holling, 2001; Holling and Gunderson, 2002) and successfully adapted to human social-ecological systems (Abel et al., 2006; Folke, 2006). It represents an ambitious attempt at presenting a framework aimed at describing and comparing the

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Fig. 2. Upper: Simulation of Snow Cover (in days) during Stadial conditions (Stage 3 Database, Barron et al., 2002). For Stadial conditions we use here the simulation for the LGM, since the Stage 3 Projekt simulation of OIS 3 cold events consistently turned out too warm (Davies and Gollop, 2003, 135). Sea level reconstructions are taken from Lea et al., (2002). Coastline shapes are taken from GEBCO_08 Grid, version 20091120,http://www.webco.net. Lower: Simulation of Snow Cover (in days) during Interstadial conditions (Stage 3 Database, Barron et al., 2002). Sea level reconstructions are taken from Lea et al., (2002). Coastline shapes are taken from the GEBCO_08 Grid, version 20091120,http://www.webco.net.
internal dynamics of social-ecological systems (Holling, 2001). The adaptive cycle model not only sheds light on situations of crises but also on the subsequent phases of reorganization. The cascade model integrates the well known process of systems changes summed up in the adaptive cycle model with climate change as a vital parameter, during all phases of change including an escalation of human reaction pattern. The basic assumption is that, over time, the structures and functions of systems may change both as a result of internal dynamics, but also due to external influences, and most notably due to climatic instability. These changes (societal and climatic) result in four characteristic phases (r-phase, K-phase, Ω-phase and α-phase) which are defined by Walker et al. (2006, 2).

The r-phase is a moment of growth with high availability of resources, the establishment of internal structures and connections, and of high resilience. During the K-phase (conservation phase) the system growth slows down, and internal structures are determined. The system is now typically less flexible and more vulnerable to external disturbances. In the model of Walker et al. (2006), the Ω-phase describes the crises, in which parts of the system breakdown and numerous functional structures and networks are subsequently reordered. The α-phase of the cycle describes the reorganization of the system. In this phase, new diversity is established, innovative strategies of resource exploitation are developed, technology and tool production are adapted, and networks are reorganized, all of which creates new structures and new contents for exchange between subsystems. The different phases of the adaptive cycle may run on different time scales: whereas the phases r and K may last for some long time periods, crises and reorganization represent extremely rapid processes (Redman and Kinzig, 2003).

Some features of the modes of reorganization described by Walker et al. (2006) are especially important when adapted as background for the cascade model. “During release and reorganization, the system is most vulnerable to change, because it is in these phases that the effects of the linkages between the system of interest and systems at other scales become more pronounced. [...] Some resources in the system are depleted following the release phase, whereas others are recombined, reused, and rebuilt. Resources can also be acquired. The dynamics of these resources and their interrelations determine how the system reorganizes.” (Walker et al., 2006: 3-4). They summarized their analysis by stating that multiple modes of reorganization are possible, and that any new modes will be most apparent during the phases that follow from the crises.

The proposed cascade model (Fig. 4) represents the hierarchic succession of different modes of system reorganization (x-axis), each of which is described in terms of climatic variability (y-axis). External agents in form of release impacts lead to vital disturbances of the socio-ecological system. These are used as markers to

Fig. 3. Adaptive Cycle Model (after Holling, 2001; Walker et al., 2006).

Fig. 4. Archaeological Cascade Model.
describe the beginning of the release phase (Ω). The model focuses on climatic instability, and hence the restricted tolerance of the system towards climatic stress is used as the basic release factor. As reaction of the system towards increasingly extreme climates, four modes of societal reorganization (σ) are defined: resistance, retreat, micro-extinction, and population breakdown. The system may end in macro-extinction, but also in subsequent immigration, or else the system may recover due to actions of the scattered remainder of the population. The primary mode of reorganization as reaction to climate change is termed ‘resistance’. In this case, the subsistence patterns can be described as a cultural adjustment within the same territory. Increasing climatic instability leads to retreat into the following reorganization mode. This corresponds to the observation that human groups may occasionally only abandon certain parts of their settlement area. Due to accelerated climatic forcing, a first reaction would be micro-extinction of peripheral groups. This mode of reaction has been described by various researchers (e.g. Stiner and Kuhn, 2006; Hulbin and Roebroeks, 2009). Finally, the breakdown of the meta-population will lead to macro-extinction, corresponding to the complete collapse of the cultural system. Basically, minor disturbances can be understand as components of the normal system development, considering the plausible assumption that “periods of gradual change and periods of rapid transition coexist and complement one another.” (Folke, 2006; 258)

In this version of the model, the optimal ability to react on climatic instability is resistance; the worst case reaction is population breakdown. Finally, in each mode of reorganization the adaptive cycle is open to change in both directions (down and upwards) and is therefore able to react towards increasing as well as decreasing climatic instability, except for the irreversible breakdown of population (macro-extinction). Limitations of dating resolution preclude strict exclusion of the possibility of the survival of a few scattered groups in the definition of population breakdown.

Changes in social structure, settlement pattern/mobility or technology are indeed highly probable as reaction towards climatic change e.g. during Greenland stadial/interstadial transitions. One main problem in applying the research model outlined above is the limited archaeological visibility of these changes. Only a very few items in the fragmentary and coarse grained Late Pleistocene archaeological archives will be sufficiently sensitive to the climatic changes to allow the necessary model testing. The majority of palaeolithic archives have only very low potential for detection of cultural changes. Nevertheless, there is the possibility that the different modes of reorganization may be identifiable as variations of techno-complexes. Under this assumption, which remains to be tested, a complete change in techno-complex would be indicative for a complete population breakdown (e.g. Blackwell and Buck, 2003).

As mentioned above, the climatic records for the period between 50 ka and 25 ka calBP (Fig. 1) show approximately 12 major climate switches. To be consequent in model application, prior to the testing phase, it must apriori be assumed that each of the 12 stadials would have forced human population to reduce their settlement area. Further, by apriori application of the cascade model, each of the observed 12 periods of rapid climate change would have triggered some kind of cultural change, even if different each time, by the hunter-gatherer populations. However, comparing the number (N = 4) of generally recognized major cultural changes (i.e. Middle Palaeolithic, Transitional Industries, Aurignacian, Gravettian, Solutrean) with the number (N = 12) of stadial/interstadial switches in the time frame under study, it becomes readily apparent that these numbers do not correspond at all well. This disagreement applies even allowing for variations in the established archaeological definitions of cultural variability that is largely based on variations in observed tool technologies. Clearly, therefore, even prior to its first application, the cascade model of cultural reaction towards climate change needs some major adjustments. Notably, why are the number of major cultural changes so strikingly different from the number of stadial-interstadial switches?

Four possible explanations are proposed:

- The temporal resolution of the archaeological record, that is largely based on radiocarbon dating, is too low to detect (rapid) climate impact on cultural systems
- The archaeological definitions of cultural techno-complexes are largely insensitive to underlying rapid societal changes.
- The climatic impact of an average stadial-interstadial switch was not strong enough to trigger the complete reaction chain, as envisaged in the cascade model.
- The resilience of human groups within their cultural system was high enough, in many cases, to buffer the climatic impact.

Allowing for such considerations and as an alternative to the clearly possible alternative that the cascade model does not properly capture the social realities of Palaeolithic hunter-gatherers – it is expected that cultural change in Late Pleistocene Europe needs a very robust climatic signal indeed before it becomes visible in the coarse grained archaeological record. The initial test is whether (at least) the major cultural switches in the Palaeolithic sequence show any indication of corresponding to (at least) the strongest climatic switches that occurred in the period under study. Clearly, the largest cultural switches are given for complete breakdown of hunter-gatherer populations; the largest climatic switches are given for Greenland stadials which show major ice-raifting events in the North Atlantic (Heinrich Events). In the following methodological case study we test this association of human population breakdown with Heinrich Events using the archaeological 14C-record of the Iberian Peninsula.

4. Iberian case study

The Iberian Peninsula has a reasonably well-studied archaeological record and numerous sets of high-resolution multi-proxy palaeoclimatological data that display good synchronicity between terrestrial and marine climatic sequences, and which are consistent in showing abrupt climate changes (Moreno et al. in press). The sequence of palaeolithic techno-complexes (Fig. 5) ranges from the Mousterian, through the Aurignacian and Gravettian, up to the Solutrean. Altogether, some 200 different archaeological sites can be associated with the time-period under study (i.e. 50–20 ka calBP, according to available radiocarbon dates). The one disadvantage of the Iberian setting is the weak evidence for the Châtelperronian, which should represent the so-called transitional industries in Southwestern Europe. The existence of the Châtelperronian is highly controversial (Maillo-Fernández, 2007).

For the purposes of this study, with compiled published 14C-data from Palaeolithic sites of Iberia, the aim is to establish a radiometric chronology on the absolute time-scale, which can be directly compared with available high-resolution palaeoclimatic records. For this purpose, the data were calibrated with CalPal-software, using the CalPal-2007-Hulu 14C-age calibration curve. For all practical purposes, this 14C-age calibration produces results that are identical to the recently established and now internationally recommended INTCAL09-calibration (Reimer et al., 2009). In consequence, the resulting archaeological chronology can be compared with the palaeoclimatic sequence. Cultural changes from one techno-complex to the next are located during Greenland stadials GS3, GS5 and GS9. These specific stadials coincide roughly with Heinrich Events (HE) with numbers HE2, HE3 and HE4. The most clearly detectable (major) cultural changes appear linked only to
those Greenland stadials that are associated with Heinrich Events (Fig. 5). However, even a brief glance at the available radiocarbon data from the Iberian Peninsula, when classified according to the major techno-complexes, demonstrates that the different cultural entities show a significant overlap in time. In previous research this temporal overlap of the \(^{14}C\)-data has often been used as an argument in support of a corresponding overlapping of underlying archaeological culture, and often also used to demonstrate contact between human populations. In addition, the overlap of \(^{14}C\)-data has been used as evidence for the assumed long coexistence of the Mousterian and Aurignacian (e.g. Carrión et al., 2008; Finlayson and Carrión, 2007; Zilhão, 2006; Banks et al. 2008a). However, the 'historical' probability of such assumed cultural patterns has been seriously contested, since this interpretation does not correctly allow for many problematic aspects of the applied radiocarbon dating method e.g. large-scale sample contamination and stratigraphic reworking (Weninger and Jöris, 2008). Not unexpectedly, therefore, in the transition from the Mousterian to the Aurignacian, and to some less extent from the Aurignacian to the Gravettian, the available (unfiltered) radiocarbon data from the Iberian Peninsula display some clearly unacceptable temporal overlap of these techno-complexes. The given overlap of \(^{14}C\)-data does not correspond at all well to the known succession of the cultural techno-complexes based on the stratigraphic observations made at a multitude of different sites. For example, based solely on radiocarbon ages, we may (wrongly) assume an overlapping of the Mousterian and Aurignacian by more than 10000 years, as shown in Fig. 5.

An inherently more reliable chronological background to the questions at stake—the reaction of human populations to rapid climate change during the Late Pleistocene period—can be provided by detailed crosschecking of given radiocarbon data against the stratigraphical evidence. The results, as provided e.g. by Jöris et al. (2003) and Zilhão (2006), are in clear contradiction to the widely assumed temporal interstratification of techno-complexes. Significantly, there is—in up to now—not one single archaeological site known from anywhere on the Iberian Peninsula, at which the postulated interstratification between Mousterian and Aurignacian, between Aurignacian and Gravettian, or Gravettian and Solutrean levels has survived this critical approach. Indeed, this applies elsewhere in Europe. Combining the critically filtered radiocarbon record with the equally critically filtered stratigraphic record, the basic conclusion is that the previously postulated chronological overlap of Upper Palaeolithic techno-complexes has been falsified at all sites. It remains to be established, by new excavations and with enhanced radiocarbon dating resolution, whether these present observations can be confirmed in all regions of Europe.

In the study region, the transition from the final Mousterian to a disputed Châtelperronian and the Aurignacian now allows for more detailed discussion. While Northern Iberia displays an archaeological record which is similar to that of Western and Central Europe, recent investigations have argued for the delayed existence of Mousterian industries in Southern Iberia, up to at least 25 ka calBP (Dolson and Harvati, 2006; Zilhão and Pettitt, 2006). Other authors argue for a shorter coexistence of Neanderthals and AMH up to ~ 30 ka calBP (e.g. Vega Toscana, 2005; Maroto et al., 2005; Vaquero, 2006). In a recent paper, Zilhão et al. (2010) has assembled documents for sites in Southern Iberia that may be of use in addressing the question of continuity or discontinuity between Neanderthals and AMH. Zilhão et al. (2010) argue that traces of Aurignacian settlement can only be seen in a later phase of the Aurignacian, dating after 36 ka calBP, and that Middle Palaeolithic settlement came to an end prior to this age limit. Following

Fig. 5. \(^{14}C\) sequence Iberia and climatic record. Upper: Summed calibrated probability of \(^{14}C\)-ages for cultural sequences on the Iberian Peninsula and France. From top to bottom: Solutrean \((N = 77, Spain and Portugal), Gravettian \((N = 70, Portugal and Spain), Early Upper Palaeolithic \((EUP, N = 81, Spain and Portugal), Middle Palaeolithic \((MP, N = 101, Spain and Portugal). Age calibration using CalPal-2007-Hulu curve (cf. Fig. 7). HE1-HE4—Heinrich Events are shown shaded with ages according to Fletcher and Sanchez Coni (2008), transferred to Greenland GISP2_Hulu, time-scale (Weninger and Jöris, 2008). Filtered and supplemented \(^{14}C\)-data assembled from the INQUA-database (Vermeersch, 2009). Note the unreliability of MP and EUP \(^{14}C\)-data (see text) and the approximate synchronicity of major changes in culturally-defined \(^{14}C\)-data assemblages both with (certain) North Atlantic ice surges as well as with periods that show significant expansion and strengthening of the Siberian High, as well as with Heinrich Events HE1-HE3. Lower: Greenland non-sea salt (nss) \([K^+\)] \(record (Mayewski et al., 1997) as proxy for the strength of the Siberian High (Rohling et al. 2002) with GISP2-age model tuned to the Hulu Cave U/Th-ages (Wang et al. 2001) by Weninger and Jöris (2008). Greenland stadial/interstadiatal numbering according to Johnsen et al. (1992) in comparison to Ice Surging on the Iberian Atlantic Margin based on C37:4 alkenone measurements from core MD01-2444 (Martrat et al., 2007).
this argument, a possible coexistence of Middle Palaeolithic complexes and Aurignacian in Iberia appears restricted to a very small time frame (in the order of max 1000 years). To date, the presence of a late Aurignacian in Southern Iberia is based on a small number of sites, that display only limited excavated surface areas and have supplied only scarce and scattered finds. However, the radiocarbon record in support of these hypotheses is still now highly limited. There are only four sites at stake, and they display highly heterogeneous radiocarbon data, in addition to one site which has a TL-date (Zilhão et al., 2010; Fig. 12).

The situation on the Iberian Peninsula is not unusual. The tremendous obstacle of how to obtain reliable $^{14}$C-ages from organic samples older than 30 ka has been stressed by numerous authors (e.g. Maroto et al., 2005; Weninger and Jöris, 2008), but the dating problems are still unfortunately often neglected in the archaeological community. As shown by recent $^{14}$C-radiometric research, the different samples (e.g. charcoal and bone) can react in many different ways, such that dating results may spread over several thousand years, even under quasi-ideal technical conditions. New laboratory methods for chemical pre-treatment (e.g. ultrafiltration and enhanced Acid-Base-Acid methods) have demonstrated that further reductions in sample contamination are feasible (e.g. Higham et al., 2006; Brock et al., 2007; Hüls et al., 2007). Notwithstanding these recent advances in chemical processing, at the present state-of-research there is still no guarantee that measured $^{14}$C-ages beyond the critical limit of ~30 ka $^{14}$C-BP have some reliable chronological meaning.

The already difficult situation is further complicated by the existence of strong secular variations of Glacial atmospheric $^{14}$C-levels which must be accounted for in the construction of $^{14}$C-based archaeological (calendric time-scale) chronologies. Previously, due to unresolved differences between data sets (van der Plicht, 2000; Bronk Ramsey et al., 2006) the INTCAL04-group (Reimer et al., 2004) refrained from recommendation of $^{14}$C-age calibration beyond 16 ka $^{14}$C-BP. More recently, the INTCAL09-group (Reimer et al., 2009) has ratified a Glacial calibration curve, which is extended to include $^{14}$C-ages beyond this limit. As shown in Fig. 6, the new INTCAL09-curve is practically identical to the CalPal-2007-Hulu calibration (Weninger and Jöris, 2008). This is not unexpected, since both curves are to some large extent based on the same (Hulu U/Th-tuned) Cariaco basin marine data (Hughen et al., 2006). Despite this agreement, there are remaining differences in curve construction, including data selection and curve smoothness. Most important, however, in the CalPal-2007-Hulu-based calibration (Weninger and Jöris, 2008) the U/Th-tuning is applied to all archaeologically relevant age models (i.e. not only Greenland ice-cores but comparisons with other climate proxies e.g. stalagmites). To conclude, then, although further refinements to Glacial $^{14}$C-age calibration are pending, there is now at least reasonable international agreement on which age models and data to use in Glacial $^{14}$C-age calibration. For ages beyond 30 ka $^{14}$C-BP the main problem is thus reduced to the known difficulties in how to obtain uncontaminated ages on samples (bone and charcoal) from the archaeological record. Going further back in time (beyond the limits of radiocarbon dating), there are other dating inconsistencies to be solved e.g. between Greenland ice-core age models (Anderson et al., 2007) and the U/Th-data derived from stalagmite proxies (e.g. Chiu et al., 2007; Feilmann et al., 2009). However, these are generally well-covered by given quantitative errors and such differences are therefore not problematic, but rather provide a challenge for further refinement of science-based archaeological chronologies.

Backed by such considerations towards the recent history and reliability of present time-scales, the overall working approach to these problems is, first, to treat archaeological radiocarbon dates older than 30 ka generally as minimum age-estimates. This caution also applies to the use of presently rather broadly defined (both in stratigraphic and cultural terms) archaeological $^{14}$C-databases available for the European Palaeolithic (e.g. as provided with the CalPal-program http://www.calpal.de or the Radiocarbon Palaeo-Lithic Database Europe v1.0 of Vermeersch (2009); cf. http://ees.kuleuven.be/geoigraphy/projects/14c-palaeolithic/download/).

An intersite comparison of cultural sequences for any area as wide as the Iberian Peninsula will indeed have to address the important question of differentiating between the (true) cultural and the (potentially distorted) site stratifications. Although a temporal coexistence of Middle Palaeolithic and Upper Palaeolithic techno-complexes over 5000 years and even more is indicated by radiocarbon dating, for many regions of Europe, up to present (and based on modern excavations) no reliable stratifications of these techno-complexes have been recorded in a single site, perhaps with one exception (Buran-Kaya, Krim) (Chabai et al., 2004).

A second conclusion is that, for the time-being, the stratigraphic method still remains by far the most reliable chronological tool for archaeological research. Indeed, in strong contrast to the presently highly error-prone natural scientific dates, the stratigraphic method is still today capable of providing some clear indication of the true temporal succession of cultural complexes. Importantly, concerning the transition from Middle to Upper Palaeolithic in
Iberia by stratigraphic analysis, different types of stratigraphies can be distinguished:

- Sites with rich Middle Palaeolithic occupation sequence typically come to an end with settlement discontinuity into the Upper Palaeolithic. At some, recoproduction - if at all - restarts later in the Gravettian or Solutrean, or even Neolithic, although natural sedimentation processes continue.
- Sites with a continuous settlement from the Middle Palaeolithic to the Upper Palaeolithic sequence. At some, a hiatus of sedimentation or sterile layers are recorded between the final Middle Palaeolithic and the early Upper Palaeolithic.
- Sites with an onset of occupation in the Upper Palaeolithic only; underlying sediments are recorded but are archaeological sterile.

These patterns clearly express different settlement histories of sites and regions within Iberia. In combination with detailed sedimentological analysis the distribution of this stratigraphical patterning could open new venues for further research independent from radiocarbon chronology.

5. Discussion

Typically, the main cultural changes in Iberia are linked to Greenland stadials that are combined with one of the Heinrich Events. Therefore, the possibility that differences between standard Greenland stadials and those associated with a Heinrich Event may exist must be discussed. The standard scheme of a DO-Event (Ganopolski and Rahmstorf, 2001) is rapid climatic amelioration followed by an extended cooling phase and subsequent restart of the cycle (Fig. 7 upper). Combined with the adaptive cycle, this process is translated into the four steps model of rapid reorganization, growth, conservation, release and subsequent reorganization (Fig. 7 lower). For the Iberian Peninsula, several reconstructions have suggested an especially strong environmental impact of HE which is more severe than during standard G-Stadials. For example, in the western part of the peninsula a severe decline of arboreal plant cover during HE is recorded (Roucoux et al., 2005) as well as decreasing temperatures and increasing aridity (Naughton et al., 2009). In southern Iberia, several environmental reconstructions show strong signs of severe aridity both along the southern coast as well as on the Mediterranean coastal sections (Sepulchre et al., 2007, d’Errico et al., 2006; Jiménez-Espejo et al., 2007; Fletcher and Sánchez Goñi, 2008; Vegas et al., 2009).

Reconstruction of rainfall patterns show that during HE 4 annual precipitation was below 100 mm/y, in parallel to a significant reduction in vegetation-cover to less than 25% of modern values (Sepulchre et al., 2007, 286). These observations provide strong evidence that the key to understanding the unusually strong impact of HE on hunter-gatherer groups recognized as change in lithic assemblages is to be sought in widespread desertification. This is especially clear in the pollen spectra from several marine cores e.g. from the Alboran Sea (Jiménez-Espejo et al., 2007; Fletcher and Sánchez Goñi, 2008) and in the Fuentillaje core (Vegas et al., 2009). The North Atlantic Heinrich Events clearly coincide with periods of strong aridity on the Iberian Peninsula. Similar observations are available from the Eastern Mediterranean (Tzedakis et al., 2004), as well as from the Levant, where the water levels of Lake Lisan display an extreme decline that also appears linked to HE (Bartov et al., 2003). Combining these results, the unusually strong environmental impact of stadial conditions associated with HE must have transformed the Mediterranean, at times, from a refugial zone with milder climate into the opposite kind of human landscape, namely a high-risk environment with semi-arid climate. Such rapid climatic switches, associated with HE all around the Mediterranean, must have had tremendous impact on settlement patterns for hunter-gatherers all over Europe, including Turkey and the Near East. This applies especially in view of human migration patterns between the different ecologies. On the Atlantic Coast of Iberia and Southwestern France, ice-rafting suggests that ice probably had a direct impact on the climate and the environment of the coastal areas and their adjacent hinterland.

In the course of G-stadials, the already reduced settlement area (with associated local or regional micro extinctions) would have been further minimized during HE, to an extent that environmental stress finally led to macro-extinction on a supra-regional level and thus, ultimately, a complete breakdown of the meta-population. However, in contrast to similar climatic arguments put forward by Sepulchre et al. (2007), aridity during HE 4 did not support, nor does it explain the assumed (based on 14C-interpretation) longer survival of Neanderthals in Southern Iberia, but would rather have produced the opposite, namely a breakdown of the Neanderthal population in that area. This conclusion is further supported by the observation that immigrant populations of Aurignacian tradition avoided southern Iberia for some long time, before they finally also colonized the south - if at all.

The climatically-deterred expansion of Aurignacian settlement itself came to an end during HE 3, with yet another population breakdown and subsequent recolonization of the Iberian Peninsula by Gravettian populations. This clear break between Aurignacian and Gravettian assemblages is generally accepted for most of Europe. As an exception, for the Swabian Alb the possibility of an in-situ transition between both techno-complexes based on a small sample of backed bladelet fragments in late Aurignacian levels and a series of early radiocarbon dates for Gravettian levels has been discussed (Conard and Moreau, 2004; Moreau, 2009). However, this interpretation is rejected by Verpoorte (2005) and Svoboda (2007) for various reasons. The main problem is the stratigraphical situation at key sites such as Geissenklösterle or Hohle Fels which display strong cryoturbation activity. In the case of the Gravettian at Geissenklösterle, refitting of stone tools provides evidence that artefacts from one single occupation layer was now...
split up by gelification into six different sublevels (Moreau, 2009). It may be further assumed that the documented vertical movement and mixing of artifacts from different levels goes in parallel with movement of corresponding sediments. Concerning the (supposedly) early radiocarbon dates from the Swabian Gravettian, it would therefore be argued that similar processes cannot be excluded for the sites in Northern Iberia, some of which show some unexpectedly early dates (Fig. 5). In conclusion, in the analysis of the $^{14}$C-data distribution from the Iberian Peninsula, even seemingly major temporal structures of the data must be interpreted as simply representing noise.

A further turnover of human populations in Iberia and Europe can be inferred for the period of HE 2 with the Solutrean (e.g. Gamble et al., 2004; Banks et al. 2008a,b). However, this time the release phase was not accompanied by complete breakdown of population. Solutrean Groups in Western Europe apparently reorganized their social system, and no immigration is recognized. In Western Europe, a new cultural tradition was established while in Eastern Europe, the Gravettian tradition continued in its transferred form as Epigravettian (Banks et al., 2009). This was the first time that in parts of Europe an HE was apparently buffered by the cultural system and it was only Central Europe that was abandoned by hunter-gatherer groups. For the first time, it appears, the cultural legacy of European hunter-gatherers was obviously split up into a Western and an Eastern World.

Although this proposed pattern of human population turnover and cultural change is in accordance with available archaeological $^{14}$C-data for the younger HE periods (Fig. 5), due to prevailing inconsistencies of the radiocarbon method the corresponding association of cultural switch and climate change during HE 4 although highly probable remains unclear. From a stratigraphical point of view, HE 4 follows in sequences from Southern Italy and the Balkan immediately on the Campagnian Ignimbrite tephra (CI) (Fedele et al., 2008; Hoffecker et al., 2008). At a few sites the CI seals so-called transitional industries. Although redepositional phenomena cannot be excluded this might indicate a cultural change before HE 4. As an alternative scenario, it might be argued that HE 5 resulted in the development of the so-called transitional industries that came to an end during HE 4. For the Near East, Shea (2008) proposes a similar association of climate forcing and population turnover during HE 5 and HE 4 and also comment on chronological uncertainties. An additional methodological complication may be the shortness of Heinrich Events: Roche et al. (2004) estimate that HE 4 had a duration of 250 years only. However, there is a question of how to define (and identify) HE 4 in different archives. Most recently, Fletcher and Sánchez Goñi (2008) have proposed data-oriented methods that are promising for further (high-resolution) sub-division of HE based on marine-archived vegetation records from the Alborean Sea. To detect such short termed events within the archaeological sequences is a real challenge. However, the same is true for many other aspects of the combined $^{14}$C-U/Th-radiometric and archaeological chronologies.

6. Conclusion

Rapid Climate Change during the Glacial period was a major factor that influences a variety of cultural, economic and demographic processes during the European Palaeolithic. In particular, and in agreement with many previous authors, climatic deterioration is put forward to explain multiple population breakdown during the European Palaeolithic, as well as to explain corresponding major cultural changes. In the Repeated Replacement Model (RRM) proposed here (Fig. 8), the most extreme climatic phases of the Glacial are identified by the occurrence of North Atlantic Heinrich Events (HE) and which are further interpreted as representing the main climatic drivers for population turnover. The strong aridity of the Mediterranean during HEs appears to have limited settlement areas to such an extent that communication networks and cultural traditions broke down and were subsequently reorganized under different socio-cultural conditions. The transition from the Middle Palaeolithic to the Aurignacian during HE 4 is one of these cultural turnover periods, which saw the final (macro-scale) extinction of Neanderthals and their widespread replacement by Anatomically Modern Humans. More
specifically, and best recognizable by comparisons with other climatically extreme Glacial periods (i.e. HE 3, and HE 2), the model excludes the survival of geographically wider (supra-regional) human networks, but it does allow for (micro-scale) survival of scattered groups. Nevertheless, it can be inferred — less from the data than from the modeling approach — that some kind of admixture between Neanderthals and incoming groups of modern humans would indeed have been possible, if only on a small scale. A long-delayed survival of Neanderthals in Southern Iberia for many thousands of years, as proposed by many previous researchers, can be excluded on the base of erroneously interpreted radiocarbon ages. Recent results of Neanderthal genome analysis stress the possibility that a small amount of interbreeding between Neanderthals and modern humans may indeed have occurred, but which appears to have taken place mainly in the Near East. Later contacts in Europe are excluded to date (Green et al., 2010).

After Neanderthal macro-extinction during HE 4, the following Aurignacian settlement system itself broke down during HE 3, showing the same kind of macro-extinction as during HE 4 (Stringer et al., 2003). Europe and Iberia then saw the immigration of a new population and the setting of again new cultural traditions that are broadly classified as Gravettian. The morphology of Gravettian populations shows a very specific and homogenous pattern in Pleistocene Europe (Churchill et al., 2000), and this supports the idea of immigration.

The Gravettian techno-complex is replaced after HE 2 in Iberia by the Solutrean. This change is different from previous population turnovers for two reasons:

First, the cultural continuum in Europe became more rugged. Whereas in Iberia a clear succession is recognized, in Central and Eastern Europe the situation is less clear. The end of the Gravettian complex saw for the first time a separation of the European cultural landscape into a western and an eastern area. In Eastern Europe, an Epigravettian, although still poorly defined in terms of technology and chronology, succeeds the Gravettian.

A second difference in comparison to previous cultural turnovers is the widely accepted evidence for a hiatus of human occupation in Central Europe after the Gravettian. The existence of such a hiatus was proposed more than 20 years ago (Weniger, 1989; Housley et al., 1997), although its intensity is still under discussion (Street and Terberger, 1999; Terberger and Street, 2002). This clearly visible regional population breakdown occurs during the Late Glacial Maximum. From the modeling perspective, this hiatus has such high visibility in the archaeological record simply because the LGM has such a long duration (many millennia). In comparison to the LGM, the HEs represent much shorter periods of climate deterioration. This readily explains why the HEs are inherently so much more difficult to recognize in the archaeological record.

Such features provide an enhanced understanding of another pattern of cultural change. Immigration of new human groups from Western Asia after the Gravettian as assumed for previous turnovers can be ruled out. As would follow from the Repeated Replacement Model (RRM), the survival of some scattered human groups would be expected, at least in certain places of Western Europe. This survival would only have been possible if cultural adaptation to the harsh environmental conditions in Europe since the beginning of the Gravettian had taken place. However, it may also be expected that during the LGM such abilities would not have been sufficiently strong to cope with the worst climate conditions in Central Europe between the Scandinavian and the Alpine ice shields.

The reorganization of human groups after the Gravettian that gave rise to the Solutrean in Iberia might also have been influenced by a migration process. For decades (e.g. Pericot, 1942; Debénath, 1994), cultural input from the Aterian of North Africa up to an immigration of humans has been discussed, albeit controversially. Recently, Tiffagom (2005) provided new input to this discussion, by proposing in addition to the well known existence of typological similarities (stemmed points and bifacial retouch) technological similarities (Levallois technique) as well between the Aterian and the Solutrean in Southern Spain. This position has been contradicted by Alcaraz and Castaño (2007). To decide on such questions, further research on both sides of the Mediterranean is crucial.

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