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PALEOCLIMATOLOGY OF THE ACHENHEIM SERIES (MIDDLE AND UPPER PLEISTOCENE, ALSACE, FRANCE). A MALACOLOGICAL ANALYSIS.

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Abstract

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The loessic series of Achenheim show an uninterrupted stratigraphical sequence dating from the middle and upper Pleistocene. They contain very abundant paleontological material, especially land snails. Statistical analysis of the malacofaunas (multivariate methods) has allowed the reconstruction of the climatic evolution of that site during this period. Five cycles have been recognized which correspond to the glacial cycles B, C, D, E and F. Comparison with the section of Cerveny kopec (Czechoslovakia) indicates:

— the existence of a major climatic event during the pleniglacial of cycle D with a general expansion of the loess steppe in Europe, an environment which later never appeared in Alsace.

— the analogy of the climatic sedimentary sequences of cycle C suggests that Alsace and central Europe belong to the same geographical entity.

— the development of Alsace to an intermediary status between northwestern and central Europe.

Introduction

Among the Central European loess sequences used by Kukla (1977) to establish his Pleistocene land–sea correlations, those from Cerveny kopec (Czechoslovakia) and Krems (Austria) both give 17 climatic cycles which have occurred since the last 1.7 million years. These two sites are remarkable in that they contain a large number of land snails with a great diversity. Based on this material relatively precise paleoecological and paleoclimatic interpretations have been proposed. At the western boundary of Central Europe, Kukla examined the Kärlich sequence between Köln and Mainz (Fig.1). However, malacological samples studied by Lozek (Brunnacker et al., 1971) did not reveal a very precise climatic history. Thus, this sequence cannot be considered as a *paleontological* connection between the Cerveny kopec and Krems series and those of western Europe e.g. Port-Morvan (Britanny; Monnier and Morzadec, 1982), St. Martin's Point (Guernesey; Lautridou, 1985) which are less thick.

Southwards in the Rhine valley, west from Strasbourg, P. Wernert (1957) studied the Quaternary sediments of Achenheim (Fig.1). Like Schumacher (1914), he recognized the following succession in the quarries Hurst and Sundhauser, from bottom to top: Rhine alluvial deposits, Vosges alluvial deposits, a yellow "canary" sandy alluvium, old loess deposits — lower, middle and upper — and a recent loess

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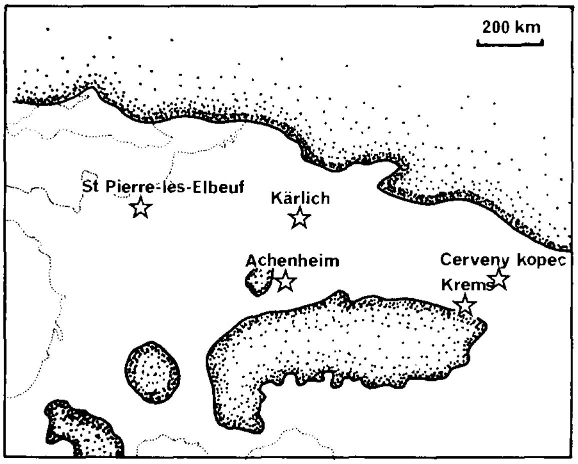

Fig.1. Location of the reference sections in the loess area. The dotted zones correspond to the limit of the maximum Pleistocene glaciation.

(Fig.2). One of the characteristics of this site is its great abundance of paleontological remains (Wernert, 1957; Heim et al., 1982).

Why should we attach importance to this deposit while it reveals only a very restricted number of climatic cycles (4–5) compared to its homologues in Central Europe? The answer is that St. Pierre-lès-Elbeuf (Normandy), which is the reference section of the loessic middle and upper Pleistocene stratigraphy (Lautridou and Verron, 1970; Sommé et al., 1980; Lautridou et al., 1983) (Fig.1), and which has been correlated with Achenheim based on stratigraphic, pedologic and paleontologic arguments (Lautridou et al., 1985), does not contain any mollusc in its loessic levels. Thus, Achenheim is the only West European loessic sequence with abundant land snails (Puisségur, 1978; Puisségur in Heim et al., 1984a).

A multidisciplinary research team has studied the Achenheim sections again with a modern approach in order to transpose the sequence to the North European Quaternary

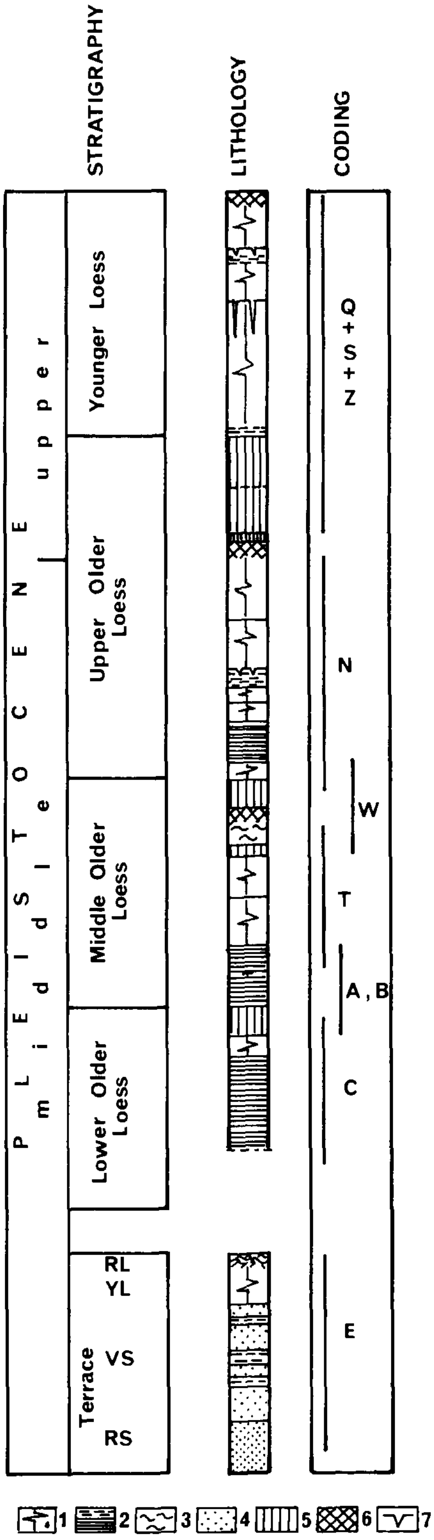

Fig.2. Lithostratigraphy of the Achenheim sequence. *1*=loess, *2*=bedded formations, *3*=colluvium, *4*=fluviatile sands, *5*=soils and humiferous deposits, *6*=Bt soil horizon, *7*=frost wedges (modified from Lautridou et al., 1985). The column coding corresponds to the coding use for the malacological associations.

stratigraphy (Heim et al., 1984a, b). The quality of the numerous malacological samples (from 218 samples, 197 were fossiliferous) with abundant material (106,662 shells compiled; Puisségur in Heim et al., 1984b) has yielded new paleoclimatic and paleoecological information which is complementary and comparable to that obtained mainly at Cerveny kopec (Fig.3).

The significance of molluscs is that often they constitute the only paleontological remains present in loess sequences. They are organisms which show very little displacement in a particular biotope. Rarely they show migratory stages. The attachment to their environment makes them ecologically very interesting. By enumerating all the species living in a particular biotope, it is possible to reconstruct from their biology and geographical distribution several environmental conditions: temperature, moisture index, vegetation, presence of water. The appearance of a new biotope in the environment changes the existing equilibrium: on the one hand some species emigrate which do not accommodate to the new conditions, on the other hand new species immigrate which were foreign to the area. Examples of such replacements have recently been found after natural or accidental disappearances of a forest which led to a complete restructuring of the environment. In Quaternary sequences, the succession of malacological communities, associations sensu Lozek and Puisségur, reveals similar variations in their composition. These fluctuations can be interpreted in the same way as today as long as the Pleistocene species have recent representatives and the fossil communities examined have not been transported over a distance of more than a few meters; if so, it must be easily noticed. The fundamental works of Lozek (1964b) and Puisségur (1976) have permitted to correlate the variations of malacofaunas with Quaternary climatic oscillations. During interglacial phases, the associations contain a great proportion of forest or semi-forest species whereas during pleniglacial phases, they comprise "foreign" species whose recent distribution is Scandinavian, alpine sensu lato or North Asiatic; they invaded with increasing glaciation (Rousseau, 1986).

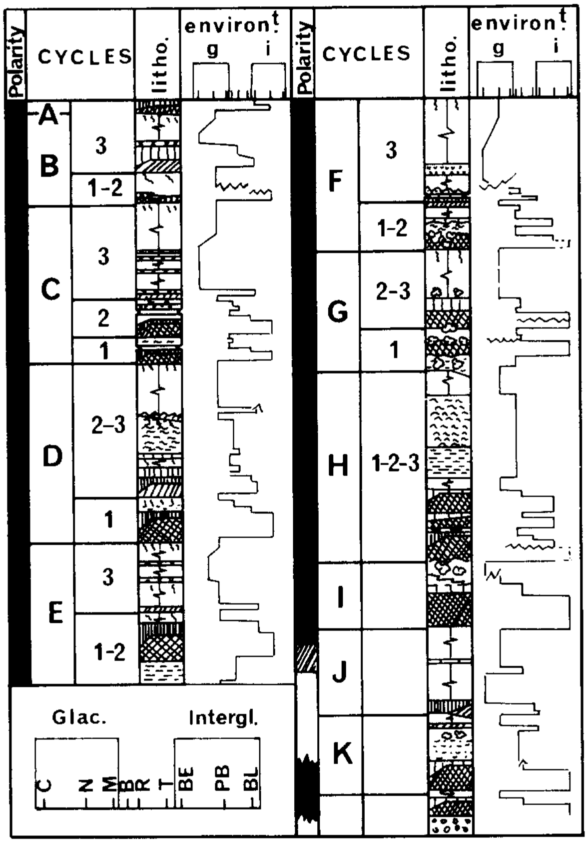

Fig.3. Lithostratigraphy of the Cerveny kopec sequence (Czechoslovakia). Same legends as in Fig.2. C = cold, N = normal, M = mild loess steppe; B = badlands; R = sparse marginal, T = thick grasslands; BE = coniferous or short-lived mixed forest on Braunerde; PB = deciduous, long lasting forests on parabraunerde; BL = deciduous forests (modified after Kukla, 1975, 1977).

Material and methods

Analyses have been made of 195 fossiliferous samples of which 61 species have been determined.

It is outside the scope of this paper to discuss in detail the techniques of studying Quaternary malacofaunas. They have been extensively described by previous authors (Lozek, 1964b; Fuhrmann, 1973; Puisségur, 1976; Stworzewicz, 1981). Nevertheless, one method in this work differs from that commonly used by European specialists. It concerns the data processing. Following the classical method, the analysis of associations is made step by step, evaluating the composition changes of a given community in comparison with the previous one. At the end of such an evaluation, a "report" is made up in which external factors occur such as the particular representation of one species, or the specialist's opinion on the climatic variations especially during this stage of development. However, the richness and abundance of the malacological material lend themselves to a more synthetic analysis based on data processing with multivariate methods. This has been tested on the Achenheim fauna (Laurin and Rousseau, 1985; Rousseau, 1985). The method used is correspondence analysis (Benzecri et al., 1973; Benzecri, J. P. and Benzecri, F., 1980). It permits symmetrical and simultaneous analysis of the samples (or associations, since to one sample corresponds one association) considered as rows and the species variables considered as columns. This analysis makes possible a simultaneous representation of the samples and the species which facilitates the interpretation of the results. With this method, the determination of the most dominant species and sample associations — that is, those that contribute considerably to the variability of each group — ensues from a numeral study of the entire material. To aid this interpretation, a hierarchical classification (Jambu, 1978; Jambu and Lebeaux, 1978) is applied to the results of the correspondence analysis. The purpose of this complementary analysis is to look at the structure of the species hyperellipsoid in multidimensional spaces and at that of the samples or associations without any a priori presumptions, and to establish a realistic partitioning in order to reconstruct the paleoenvironment.

The importance of the correspondence analysis is that it does not assume the existence of any relationship between the variables or the samples. However, the data list must be homogeneous concerning the values, so it is necessary to code carefully the original data. In certain associations, it is possible that some species show large differences in representation, thereby introducing important numerical gaps which can disturb the analysis. The coding procedure consists in transforming the data values as abundance classes on a logarithmic scale. Thus the base used (2) permits a classification into 13 classes:

0: absence of species
1: 1–2^1 means 1–2 individuals
2: (2^1+1)–2^2 means 3–4 individuals
3: (2^2+1)–2^3 means 5–8 individuals

12: $(2^{11}+1)$–2^{12} means 2049–4096 individuals.

In each case the number of individuals is replaced by the number of the corresponding class. Thus, the values fluctuate between 0 (absence) and 12 (maximum representation: from 2049 to 4096 individuals) (Laurin and Rousseau, 1985). Such a coding retains the patterns of variations in representation, while reducing the numerical differences between well and bad represented species.

Results

Interpretation of the results of the correspondence analysis depends on the contribution of the species and of the associations to the so-called "inertia" — that is, to their variability (the terminology of correspondence analysis follows Benzecri et al., 1973 and Greenacre, 1984). These contributions can be positive and plot on the positive part of the axis or factor, or negative and plot on the negative part of the axis. Acquainted with the ecological, biological and biogeographical characteristics of a species, it is thus possible to characterize each correspondence analysis axis.

Correspondence analysis

The four first axes represent 37.79% of the total inertia or variability of the cloud, or total data, that is 12.65, 10.24, 8.24 and 6.67%, respectively. The theoretical average contribu-

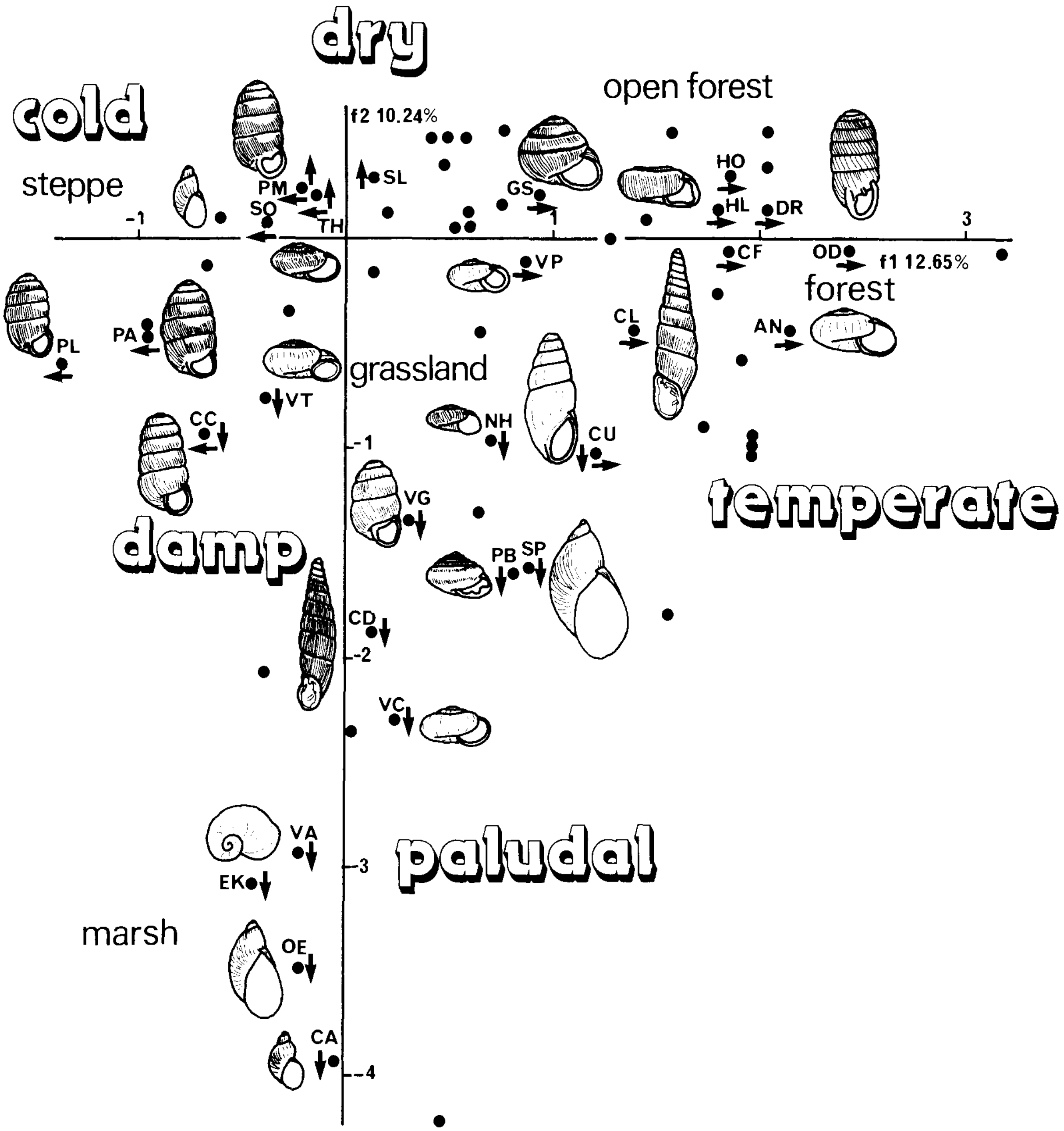

Fig.4. Correspondence analysis of the malacofaunas of Achenheim. Plot of the species (variables) on the first factor plane (axes 1–2). The dark arrows indicate how the species contribute to the "inertia" of the hyperellipsoid. Concerning the ecological characteristics of the species, four poles can be defined: temperate, cold (temperature gradient parallel to the axis 1; dry, and damp (moisture gradient parallel to the second axis). *AN*= *Aegopinella nitidula*, *CA* = *Catinella arenaria*, *CC*= *Columella columella*, *CD*= *Clausilia dubia*, *CF*= forest *Clausilias*, *CL*= *Cochlodina laminata*, *CT*= *Chondrula tridens*, *CU*= *Cochlicopa lubrica*, *DR*= *Discus rotundatus*, *EK*= *Eucobresia kochi*, *GS*= great species (*Arianta arbustorum*, *Bradybaena fruticum*, *Cepaea* sp.), *HO*= *Helicodonta obvoluta*, *HL*= *Helicigona lapicida*, *HS*= *Helicella striata*, *NH*= *Nesovitrea hammonis*, *OE*= *Oxyloma elegans*, *OD*= *Orcula doliolum*, *PB*= *Perforatella bidentata*, *PA*= *Pupilla alpicola*, *PL*= *P. loessica*, *PM*= *P. muscorum*, *PP*= *Punctum pygmaeum*, *SL*= Slugs, *SO*= *Succinea oblonga*, *SP*= *S. putris*, *TH*= *Trichia hispida*, *VC*= *Vitrea crystallina*, *VA*= *Vertigo parcedentata*, *VG*= *V. genesii*, *VY*= *V. pygmaea*, *VO*= *Vallonia costata*, *VP*= *V. pulchella*, *VT*= *V. tenuilabris*.

tion if all species contributed equally to the variability is 1.6% (1/61 × 100). As regards the associations, the theoretical threshold is 0.5% (1/195 × 100).

On the first axis, the configuration of the points is due, according to the negative coordinates, to the great contributions from *Pupilla alpicola* (8.7%), *Succinea oblonga* (7.9%), *Pupilla loessica* (3.1%), *Columella columella* (2.9%) and *Trichia hispida* (2.3%) (Fig.4). On the positive side, there are on the axis forest *Clausilias* (11.2%), big species (grouping together of *Cepaea* sp., *Arianta arbustorum* and *Bradybaena fruticum*) (8.5%), *Discus rotundatus* (7.2%), *Helicodonta obvoluta* (5.3%), *Aegopinella nitidula* (5.4%), *Orcula doliolum* (3.4%), *Vallonia pulchella* (4.3%), *Pupilla muscorum* (2.7%), *Cochlicopa lubrica* (2.7%), *Helicigona lapicida* (2.3%) and *Cochlodina laminata* (2.0%) (Fig.4). The first axis thus distinguishes, on the one hand, foreign species characteristic of cooling (*Pupilla alpicola*, *P. loessica* and *Columella columella*) and, on the other hand, species whose ecological characteristics suggest a temperate environment (arboreal vegetation) (Fig.4).

On the second axis, the patterns are due to the great contributions of species that mainly have negative coordinates. These are *Catinella arenaria* (11.9%), *Vitrea crystallina* (11.5%), *Vertigo parcedentata* (8.7%), *Oxyloma elegans* (8.5%), *Succinea putris* (6.7%), *Columella columella* (6.2%), *Eucobresia kochi* (5.1%), *Perforatella bidentata* (4.5%), *Vallonia tenuilabris* (3.5%), *Clausilia dubia* (3.4%), *Vertigo genesii* (2.8%), *Nesovitrea hammonis* (2.5%), *Cochlicopa lubrica* (2.5%) and *Pupilla alpicola* (2.0%) (Fig.4). Those with the positive coordinates only include *Trichia hispida* (2.4%), *Pupilla muscorum* (3.4%) and the slugs sensu lato. These contribute to the configuration of the points. The ecological characteristics of the species with a large contribution on the second axis reveal a discrimination between paludal or greatly hygrophilous species and those with variable characteristics (Fig.4).

On the third axis, species with positive coordinates, are *Pupilla loessica* (12.8%), *P. alpicola* (9.0%), *Aegopinella nitidula* (5.5%), *Discus rotundatus* (5.3%), *Helicodonta obvoluta* (5.2%), forest *Clausilia* (4.5%), *Orcula doliolum* (3.7%) and *Helicigona lapicida* (2.6%) (Fig.5). Those with negative coordinates are *Punctum pygmaeum* (9.8%), *Vallonia costata* (5.7%), *Helicella striata* (4.2%), *V. pulchella* (4.1%), *Vertigo pygmaea* (3.8%) and *Chondrula tridens* (3.7%). These have a great contribution to the axis (Fig.5). The discrimination of the species along this axis is rather peculiar. The species on the positive side have varied attributes. *Pupilla alpicola* and *P. loessica* live in open environments. The former prefers marshy mountain places, the latter loess steppe. *A. nitidula*, *D. rotundatus*, *H. lapicida*, *H. obvoluta* and *O. doliolum* occur frequently in arboreal environments. The same remark can be made for the negative sector, as it groups species with a high moisture requirement: *Vallonia costata* and *V. pulchella*, and other much less hygrophilous: *C. tridens*, *H. striata*, *P. pygmaeum* and *V. pygmaea*. In fact, the third axis distinguishes species of extreme environments (from a climatic point of view: temperate and glacial) from those "intermediate" ones. The apparent complexity of these results is due to the interpretation of the diagram, axis after axis, of the multidimensional space (Fig.5).

The shape of the cloud of the species points on the fourth axis is due to the negative contributions of *Trichia hispida* (4.7%) and *Succinea oblonga* (4.1%). On the positive side, *Pupilla loessica* (47.0%), *Punctum pygmaeum* (11.8%), *P. alpicola* (5.9%), *P. sterri* (5.8%), *Vallonia pulchella* (3.3%), *Vertigo pygmaea* (1.9%) and *Helicella striata* (1.8%) all contribute to the inertia. The important point on this axis is the discrimination of the *Pupilla* fauna, characteristic of the loess steppes. No abundant species with large numbers occur where those of the genus *Pupilla* dominate (Lozek, 1965a, b). Such associations are rare at Achenheim where they only occur in the white loess of the third loessic cycle (old middle loess of the authors). *S. oblonga* and *T. hispida*, on the other hand, are represented throughout the sequence of Achenheim except for occasional

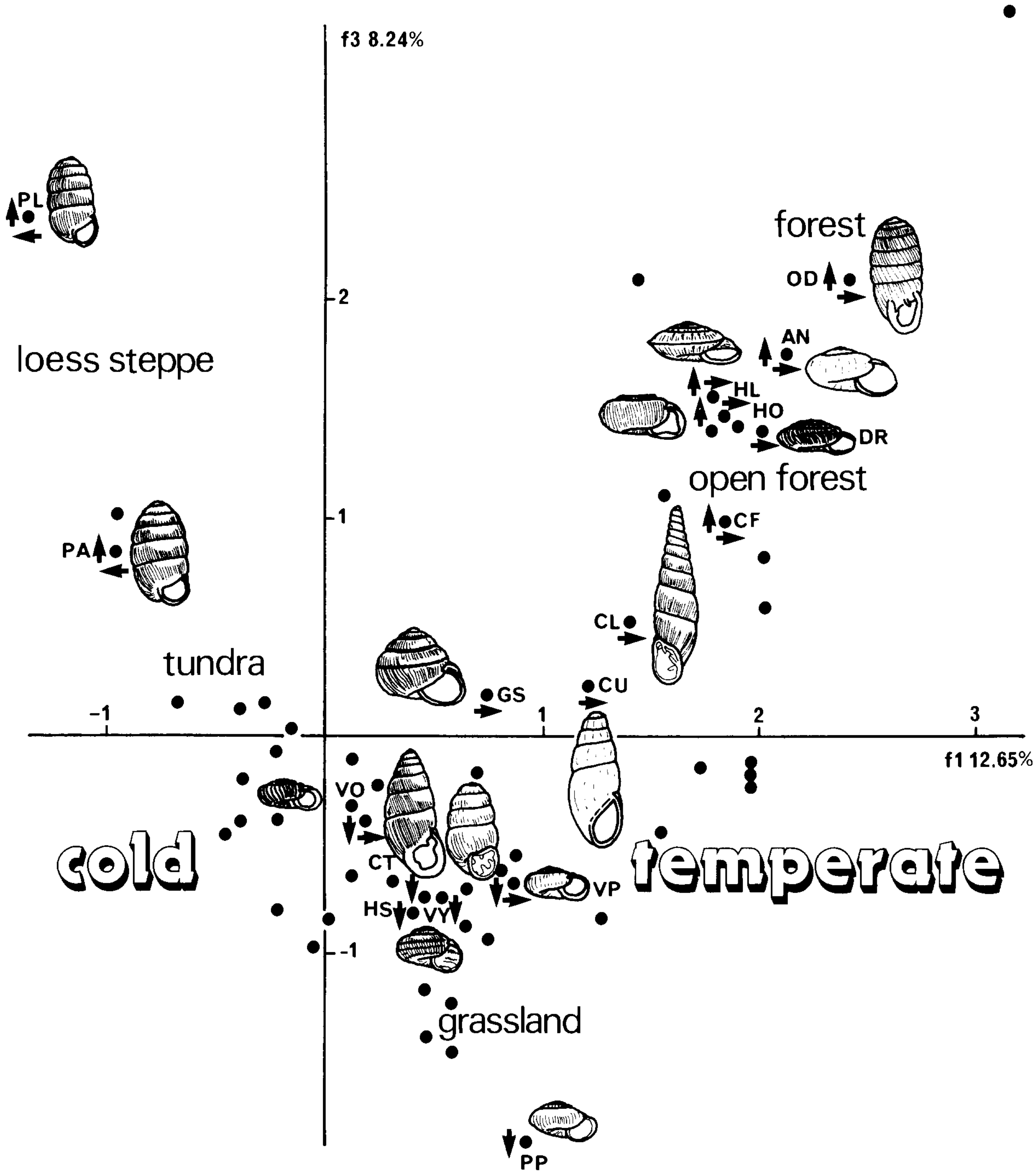

Fig.5. Correspondence analysis of the malacofaunas of Achenheim. Plot of the species (variables) on the factor plane 1–3. (Same legend as for Fig.4).

samples. These species are relatively ubiquitous. They constitute, with *Pupilla muscorum*, the background noise of the analysis.

On the first plane formed by axes 1 and 2, the species are plotted between four extremes: a temperate one determined by the forest and semi-forest species (positive coordinates axis 1); a cold one determined by the foreign species of open environments (negative coordinates axis 1); a very damp one characterized by paludal or highly hygrophilous species (negative coordinates axis 2); and a xerothermic one on the positive side of the second axis (Fig.4). The arrangement of the species between these four endpoints is not uncertain but reveals the ecological characteristics of each of them. The distribution of the species on the plane formed by axes 1 and 3 is peculiar (Fig.5). The diagram looks like a parabola. It is a particular effect in correspondence analysis called the "Guttman effect" (Benzecri et al., 1973; pp. 192–198): the third axis is a quadratic function of the first one. For a coherent interpretation of the results, it is necessary to analyze the results obtained for the two axes. In that case it is easier to understand that on the third axis, according to the positive coordinates, species are plotted side by side with radically different ecological characteristics. Each end of that parabola corresponds to an optimal climatic condition: Pleniglacial or Interglacial. The species in intermediate position reveal climatically transitional conditions. The distribution of paludal or greatly hygrophilous species on the factor plane of axes 1–3 shows the presence of taxa indicating a cold climate: *Catinella arenaria*, *Clausilia dubia*, *Eucobresia kochi*, *Vertigo alpestris*, *V. genesii*, *V. parcedentata* and *V. substriata*, or a temperate one: *Cochlicopa lubrica*, *Perforatella bidentata* and *Vertigo antivertigo* (Fig.5).

The interpretation of the fauna distribution is similar to that of the species. On the first plane (axes 1–2), the malacological associations are plotted and follow an orientation that is parallel to the first axis (Fig.6). According to the negative coordinates, associations with foreign well represented species are discriminated: T03 (2.0%), T05 (2.3%), T04 (2.5%) where *Pupilla alpicola* and *P. loessica* dominate; Q11 (1.6%), Q12 (1.2%), Q13 (1.5%), Q14 (1.1%), Q19 (1.3%) and E06 (1.1%) where *Columella columella* and *Pupilla alpicola* dominate. On the positive side of the first axis, associations with a large contribution are relatively numerous: W05 (11.2%), W06 (4.8%), T09 (3.7%), W09 (2.9%), T08 (2.6%), T10 (2.2%), A-4 (1.7%), W07 (1.7%), N15 (1.5%), W08 (1.3%), W03 (1.8%), A-1 (1.1%), Q26 (1.0%) and A-5 (1.0%). Unlike associations characteristic of cold climatic conditions which as a whole contained 13 species, these ones contain 46 species from which *Aegopinella minor*, *Arianta arbustorum*, *Bradybaena fruticum*, *Cepaea* sp., *Cochlodina laminata*, *Discus rotundatus*, *Ena montana*, *Helicigona lapicida*, *Helicodonta obvoluta*, *Nesovitrea hammonis*, *Perforatella bidentata*, *Punctum pygmaeum* and *Trichia villosa* indicate the occurrence of arboreal environments and hence a temperate climate. The moisture conditions are variable and are largely reflected by the second axis. Two communities present large contributions: ESR (33.6%) and ELC (17.9%). They belong to the fluviatile sequence of the Rhine Terrace at the base of the Achenheim series. Both reveal a large percentage of paludal species (*Oxyloma elegans*, *Pupilla alpicola*, *Vertigo antivertigo*, *V. genesii*, *Succinea putris*) or of hygrophilous species (*Succinea oblonga*, *Vertigo substriata*) or of very damp grassland (*Catinella arenaria*) (Fig.6).

Cluster analysis

To understand the structure of the hyperellipsoid of sample points and to give a precise and comprehensive interpretation in ecological and climatical terms, I have made a cluster analysis (agglomerative hierarchical classification) from the coordinates of the associations obtained for the first four axes of the correspondence analysis.

Nine clusters are distinguished by taking the value 1% of the relative inertia into account in comparison with the total inertia of the cloud.

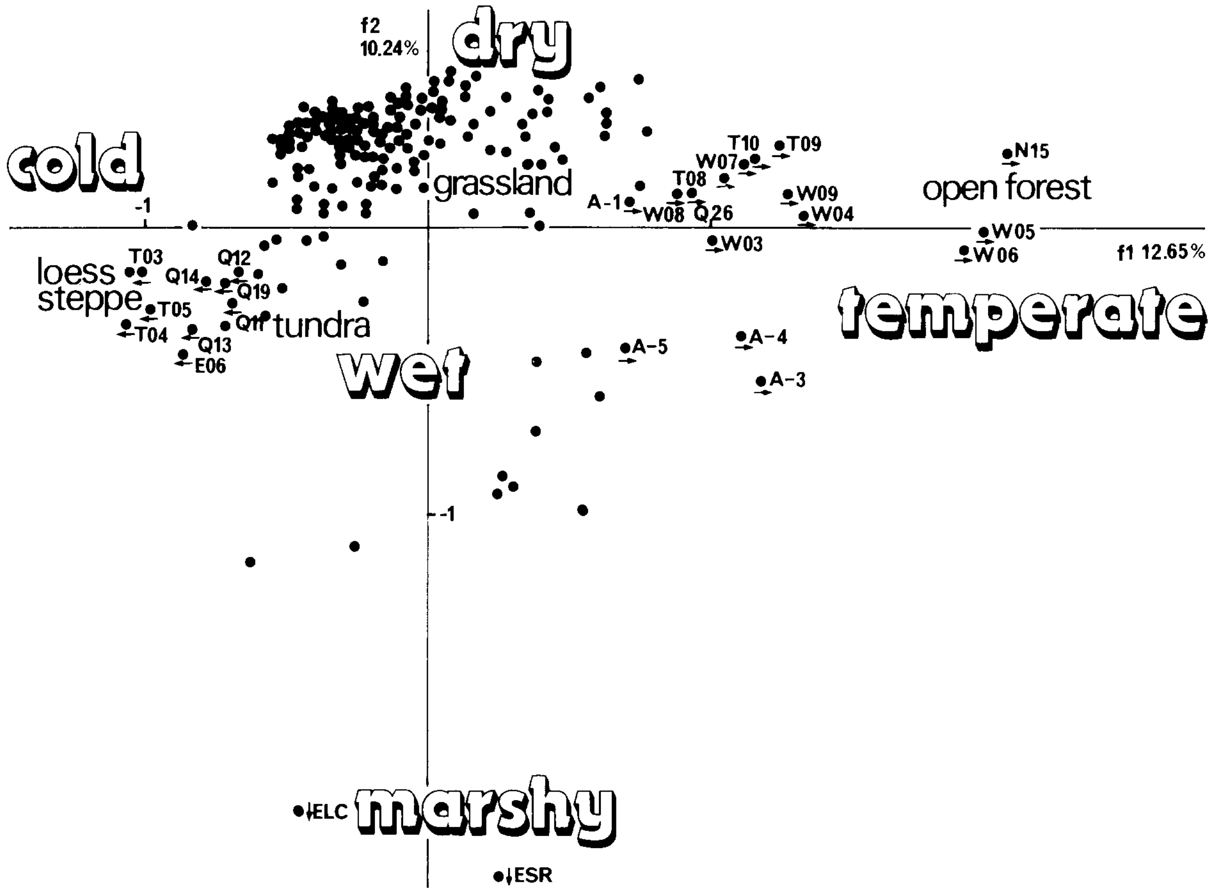

Fig.6. Correspondence analysis of the malacofaunas of Achenheim. Plot of the malacological associations (individuals) on the first factor plane (axes 1 2) (same legends as for Fig.4).

These are the classes 379, 368, 377, 344, 380, 376, 381, 378 and 375 (Fig.7). The analysis of the relative contributions of the axes to the highest clusters reveals the preferential discrimination of the associations according to the first three ones (Fig.7). This confirms the importance of these three axes previously indicated by the interpretation of the results of the correspondence analysis.

Interpretation

The interpretation concerns mainly the malacological associations. It is based on the recognition of nine classes, on their examination in terms of biological compatibility, and on the analysis of their distribution on the first

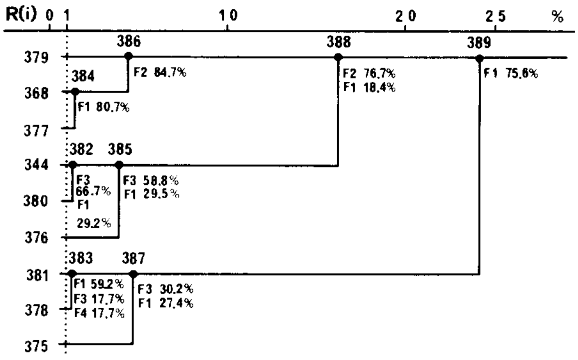

Fig.7. Agglomerative hierarchical classification of the malacological associations based on the results of the correspondence analysis. Major classes (1% of the relative inertia) and the contribution of the main factors to the discrimination of the highest classes are shown.

factor plane (axes 1–2) of correspondence analysis. Finally a palaeoclimatic interpretation will be offered based on these results and compared with the climatical variations obtained at Cerveny kopec near Brno in Czechoslovakia.

Two major dichotomies are easily distinguishable on the hierarchical classification tree (Fig.7). The former corresponds to class 388 which groups together, on the one hand, classes 379, 368, 377 and, on the other hand, classes 344, 380 and 376. The highest contribution to the dichotomy of the high class 388 is from the second factor axis (comparable to a moisture gradient detected from the results of correspondence analysis). Class 386 assembles the associations whose primary characteristic is a very damp environment. On the other hand, class 385 groups together the associations representing temperate climatic conditions. Inside this cluster, the classes suggest the occurrence of an arboreal vegetation, not always abundant in the same way that is missing in class 376 (Fig.7).

This initial discrimination corresponds to a purely statistical interpretation of the results. Nevertheless according to the ecological characteristics of the species represented in the classes, a new discrimination can give supplementary information. In this way class 380 can be divided into two subcategories: 374 and 339 which correspond to different moisture conditions: less damp for the former and damper for the latter (Fig.8). A priori, this differentiation may seem insignificant as it corresponds to relative variations in moisture. Yet it assumes a particular interest when considering the paleoclimatical interpretation of the complete Achenheim sequence.

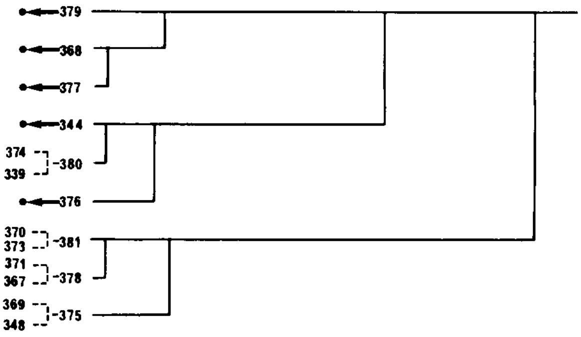

Fig.8. Interpretation of the classification of the malacological associations from the ecological data. Dotted lines represent the new recognized classes. The black arrows indicate the retained classes.

The second major dichotomy corresponds to the high class 389 for which the first axis of the correspondence analysis contributes greatly (75.6%). The two high classes concerned are C 388 and C 387 (Fig.7). The former corresponds to the first major dichotomy previously defined. The latter groups together the associations of which the results are contrary to those of the temperate climate communities. They reveal climatic conditions which are going to the maximum of cooling. Class 375, according to the composition of its associations, indicates Pleniglacial conditions: the foreign species are abundant. As previously, it is possible to distinguish two subcategories: classes 369 and 348 (Fig.8). They represent two classical associations in the literature: the *Pupilla* faunas (348) and the *Columella* faunas (369). The former is characteristic of steppe loess where a small number of species of the genus *Pupilla* dominate. The latter is considered as representative of a tundra environment, damper than the former and richer in species. In the same way, according to the composition of the associations, the class can be split up into two subcategories with a variable moisture tolerance: 370 (less damp) and 373 (damper) (Fig.8). They represent relatively cold conditions but less pronounced than previously. In environmental terms these associations characterize environments with a poor and scattered vegetation that can be termed as a proto-loess steppe (C 370) and as a proto-tundra (C 373). Class 378 expresses less cold climatic conditions than the previous open environment. However, two well distinct subcategories can be recognized: classes 371 and 367 (Fig.8). The former represents a cold climate which, on a relative thermal scale, would correspond to the beginning of a cold period and thus would specify the end of an intermediary climatic period between Interglacial and Pleniglacial. The latter, on the same scale, suggests milder thermal conditions. But its main characteristic is that it represents a very xerothermal environment. In fact this class is plotted on the positive pole of the second axis (hygrometric axis).

Thus, from nine major classes statistically determined originally we now have 13 basic classes for the climatic and environmental interpretation of the Achenheim sequence.

From a climatic point of view, 7 major assemblages can be determined.

Temperate climate

(1) C 344: open forest associations.
(2) C 399: open environment associations with the occurrence of well represented trees and bushes, slightly damp.
C 374: associations identical to the former but damper.

"Intermediary" climate

(3) C 376: associations of open environment without any arboreal vegetation, a not very damp grassland.
C 377: associations of damper grassland.
(4) C 367: associations of very dry grassland.
(5) C 371: associations of open environment, grassland, where often occur, though in small quantities, *Columella columella* and *Pupilla alpicola*.
C 379: associations of the same type as above but with a damper and even marshy character.

Glacial climate

[in comparison with the climatic interpretations of the sequences of Cerveny kopec and Krems presented by Kukla (1975, 1977)]
(6) C 370: associations of open environments with scarce vegetation and low humidity which can be qualified as *proto*-loess steppe. This is the *Pupilla* fauna in embryonic state.
C 373: associations of open environments with a scarce vegetation and higher humidity than the former, which can be qualified as *proto*-tundra. This is the *Columella* fauna in embryonic state.
C 368: associations of open environments with a scarce vegetation but higher humidity: damper, marshy. These associations recall those of class 379 under colder climate.
(7) C 348: associations of environment with a scarce non arboreal vegetation and moderate humidity. Coldness optimum in the loess steppe (*Pupilla* fauna).
C 369: associations of environments with a scarce vegetation, occurrence of some bushes and a higher humidity than above. Coldness optimum in the tundra (*Columella columella* fauna).

Discussion

Climatic and environmental evolution

The Rhine Terrace (Fig.9)

The Terrace sequence suggests that the fluviatile sediments have settled in relatively cold climatic (Rhine sands) and glacial (Vosges sands) conditions. The top indicates a relatively strong warming up as shown by the red loam of the plateaus ("limon rouge des plateaux"). Should this level be interpreted as the interglacial Achenheim IV or not? Although containing temperate species, its stratigraphical position and outcrop conditions do not permit a conclusion. Nevertheless, it is possible to integrate it into the first interglacial pedocomplex of the Achenheim sequence among which it would be the only recognized element.

From the environmental point of view, the Terrace sequence reveals the change from a very damp open environment, with the occurrence of water, to a clearly marshy environment with scarce vegetation. The water disappears relatively quickly and is replaced by a tundra characterized by *Columella columella* faunas. In this type of environment the more marked coolings occur. Finally the transition between cold open environments and temperate ones with sparse arboreal vegetation is relatively quick.

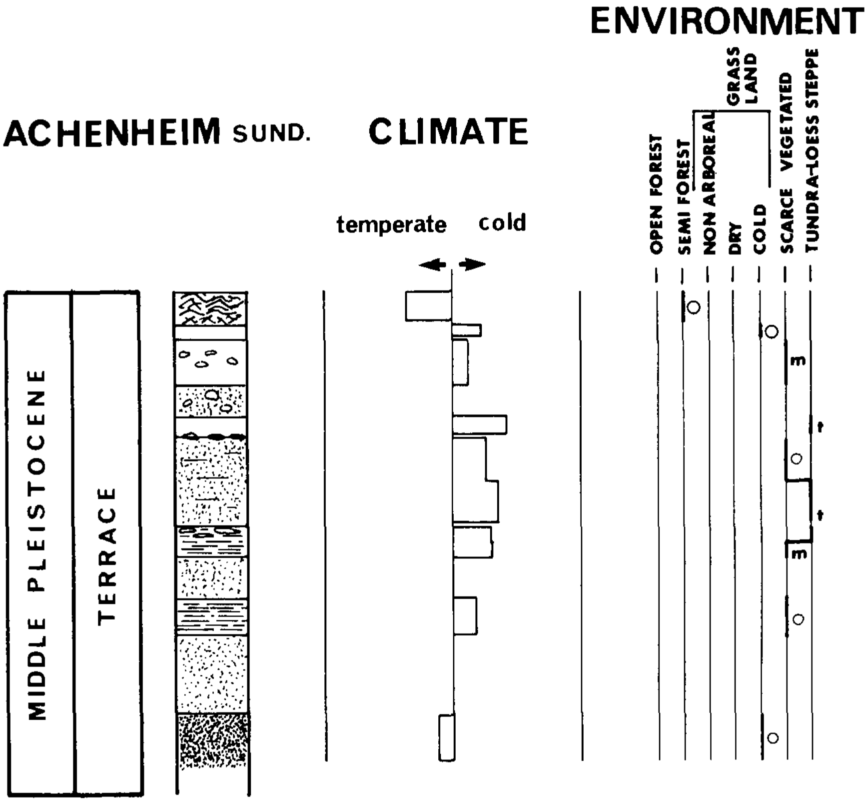

Fig.9. The Rhine Terrace sequence. On the left, lithostratigraphic column (same legend as in Fig.2). At the center, *Climate* = plot of the associations on the first factor axis of the correspondence analysis interpreted as a climatic axis. The central line corresponds to the mean position of the associations between characteristics of the interglacials on the one hand and those of the maximum coolings on the other hand. On the right, *environment* = graphic representation of the succession of paleoenvironments after the results of the malacological classification. Dark circle = less damp, white circle = damper, *m* = marshy, *s* = loess steppe, *t* = tundra.

The Lower Older Loess (Fig.10)

This incomplete sequence is represented by layered sediments that Puisségur (1978) qualified as of the "Lehmbröckelsande" type. The climatic conditions were cold without reaching the intensity of the previous coolings. Although a particular tendency cannot be seen, many little variations have been found. The sequence ends with a kind of warming up.

Environmental analysis suggests the succession of open damp environments when cold climatic conditions (end of the intermediary climatic phase) alternating with environments with scarce vegetation and low humidity, without any tree or bush and of steppic type. Such alternations are characteristic of the Lehmbröckelsande which Lozek (1964a, 1976) defined when he determined the climatic impact on the sedimentary cycle of the loessic series.

The Middle Older Loess (Fig.11)

The climatic evolution recorded by this sequence is relatively simple as it reveals the following succession: an interglacial complex, a transition phase represented by "Lehmbröckelsande" with a progressive climatic degradation, the Pleniglacial represented by *Pupilla* associations, then a new transition phase with a tendency to gradual warming. The environment during the interglacial complex was first a damp grassland without any arboreal vegeta-

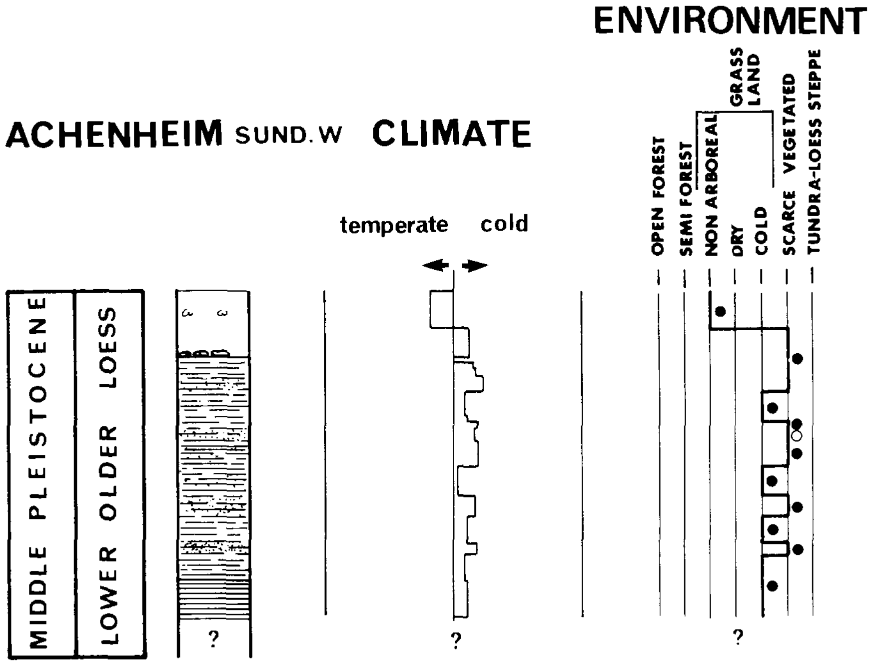

Fig.10. Lower Older Loess sequence (same legend as Fig.9).

tion, corresponding to the end of a transition phase between the Pleniglacial and Interglacial. Afterwards an open environment was formed with variable humidity where trees or bushes occurred. The interglacial ends with the change to "intermediary" environments of variable humidity indicating a progressive decreasing temperature. This period corresponds to the sedimentation of bedded deposits more characteristic and more similar to the "Lehmbröckelsande" of the Central European sequence. However, below these gravel sands there is no "marker". The Pleniglacial (maximum of the cooling) appears suddenly with a clearly loess steppe environment. At the end of the sequence, the environment changes also abruptly to a transition characterized by open damp conditions, then a dry grassland with a progressive warming up. Although relatively short, the Middle Older Loess sequence is nevertheless very useful as it gives prominent logical and relatively complete information on the succession of climatic and ecological events.

The Upper Older Loess (Fig.12)

This climatic sequence comprises the following succession: at the bottom, an interglacial complex with two climatic optimums, indicating a slow and progressive degradation of the climate. It should be noted that the brown soil reveals very contrasted conditions between its base and its top. Then the climate is "intermediary" — that is, mean thermal conditions between temperate and maximum of the cooling. This phase ends with a relatively short pronounced cooling. It is followed by an episode of relative warming up, clearly marked at its top. Finally, with the loessic sedimentation rather cold climatic conditions appear with little variations. It is important to note that the sequence never shows a very pronounced cold such as in the Terrace and the Middle Older Loess sequences. Nevertheless, it seems that this sequence is complete as it is introduced here (Heim et al., 1984a, b).

The interglacial complex begins with a rather damp grassland, without any arboreal vegetation, changing to an open environment,

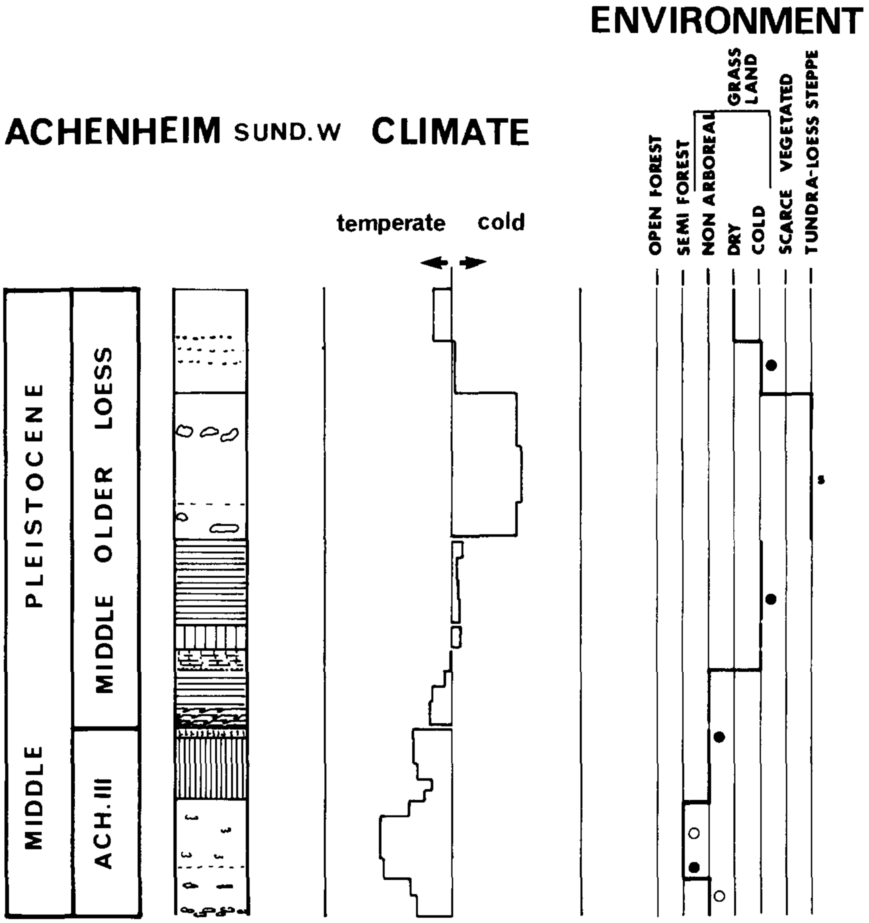

Fig.11. Middle Older Loess sequence (same legend as Fig.9).

still damp where trees and bushes arrive at an open forest which marks the climatic optimum. This interglacial complex is characterized by a double alternation of open forest–arboreal grassland. The end of the complex is marked by the relatively sudden appearance of an "intermediary" environment: a dry grassland.

The transition phase is marked by the alternation dry grassland–open damp environment of the type characteristic of the beginning of the cooling. Cooling passes from a cold grassland of this type into a scarce vegetated environment, always in moist conditions, with some bushes (Proto-tundra).

The following phase begins in conditions relatively analogous to the former: succession dry grassland–proto-tundra. Then a rapid change appears to transition conditions with the alternation dry–damp without arboreal vegetation grassland. Finally it ends with an open forest environment as shown by the occurrence of a great number of individuals belonging to *Cepaea* sp. and *Arianta arbustorum* but also by the occurrence of *Helicodonta obvoluta*, forest *Clausilias* and *Discus rotundatus*. This episode is relatively brief as it is immediately followed by the development of a dry grassland. In these conditions, it is not possible to qualify it as an open forest but rather as the development of arboreal vegetation which permitted semi-forest land snails to live and grow.

The loessic sedimentation begins with a less damp open environment changing rapidly to a

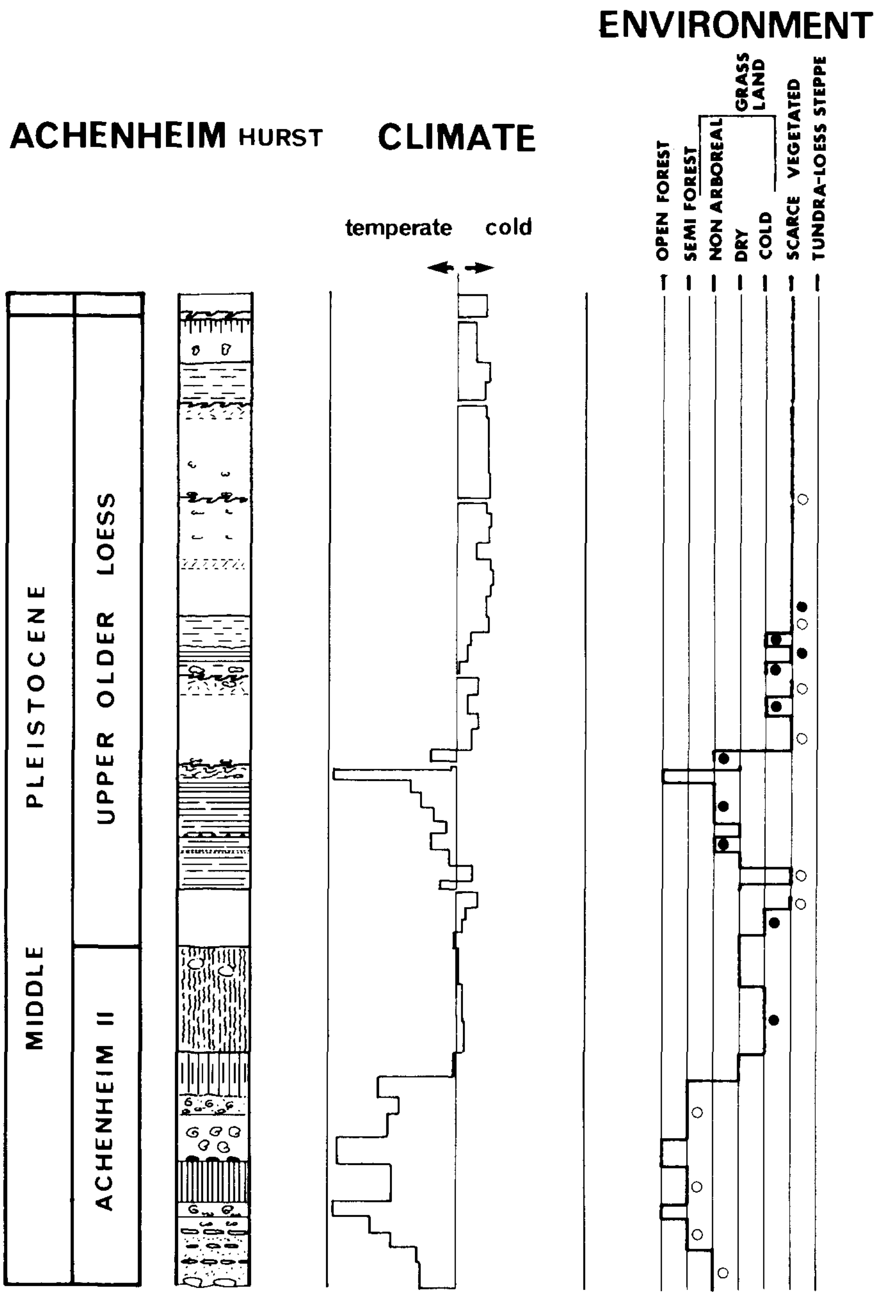

Fig.12. Upper Older Loess sequence (same legend as Fig.9).

proto-tundra. It is followed by the transition of cold damp grassland characteristic of the beginning of cold conditions with scarce vegetation to the type proto-tundra or proto-loess steppe. The rest of the sequence which agrees with the thermal maxima recorded indicates a proto-tundra.

The particularity of this sequence is the succession of six climatic phases corresponding to clearly precise sedimentary conditions.

The interglacial complex contains at the bottom a loamy sediment topped by a brown soil (phases 1 and 2). The transition period from dry to cold and again dry grassland is suggested by loamy sediments and corresponds to a third phase. It is surmounted by a new phase, the fourth which, according to the loessic level, by its sedimentological characteristics and its climatic features, is comparable to the "marker" of the climatic-sedimentary cycle of the loessic series as defined by Lozek (1964a, 1976). Finally, the bedded levels of the type "Lehmbröckelsande" and the overlaying loess deposits correspond to a fifth and a sixth phase. In summary, the Upper Older Loess shows a climatic sedimentary sequence exactly similar to those observed in central Europe: "Lössumlagerung, Parabraunerde, Schwarzerde, Marker, Lehmbröckelsande, Löss". Thus, it seems that the period of deposition of the Upper Older Loess is characterized by great affinities between Alsace and the Central European domain.

The Younger Loess (Fig.13)

The malacological fauna is not good represented in pedocomplex Achenheim I. However, the few existent data corroborate the palynological results of Heim (in Heim et al., 1984a, pp. 25–26). The malacofauna suggests a climatic degradation followed by a return to mean ("intermediary") climatic conditions. A slight warming up precedes the cooling attested by the loessic sedimentation. First there is a little marked cold of which the intensity is equal to the cold of the Upper Older Loess. It is at the top of the sequence that the cold optimums appear. They can be divided into two groups (the Lower Younger and the Cover Loesses) on each side of the "Kesselt" mark level (Sommé et al., 1986). The optimums in the Cover Loess are the most important coolings regarding intensity. They are separated by a period characterized by mean thermal conditions. The terminal warming up corresponding to the Holocene appears relatively suddenly after the last cold peak.

From the environmental point of view, in pedocomplex Achenheim I the start of climatic degradation is an open moist environment of the type characteristic for the beginning of cooling, the optimum corresponding to a proto-tundra environment. This is in agreement with the palynological observations indicating the degradation of an environment with a "*surrounding*" forest. Similarly, the environmental change as shown by pollen indicates a tendency to increasing dryness at the end of the pedocomplex. This is confirmed by the land snails which point to a dry grassland.

The first part of the loessic sedimentation begins with a scarce vegetated environment with moist conditions; only a few rare bushes are present (proto-tundra). The first half of this period is marked by a little warming up in damp cold grassland (beginning of the cold). The phase with the cold optimums of the Lower Younger Loess is related to the alternation of tundra environments represented by the *Columella columella* associations and of scarce vegetated environments with variable humidity (proto-tundra and proto-loess steppe). In the Cover Loess, the more pronounced cooling of the sequence begins after the change from tundra to loess steppe environments. A little warming up takes place immediately thereafter, always in rather poor moisture conditions: dry grassland. Then the development to a second optimum is accompanied by the following succession: proto-tundra, damp cold grassland (beginning of the cold), tundra. Finally, the transition to the Holocene Interglacial goes from a proto-tundra directly to a damp open environment with the occurrence of arboreal vegetation.

Particular attention should be payed to the results obtained between the two optimums of the Lower Younger Loess. The significance of each association is low. Only a small number of individuals has been preserved. The number of compiled species varies between three and five, their strengths varying from 6 to 17. What interpretation can be proposed? This under-representation is common at Achenheim as all the sampled sections of this unity, though located at different sites of the quarry (Sommé

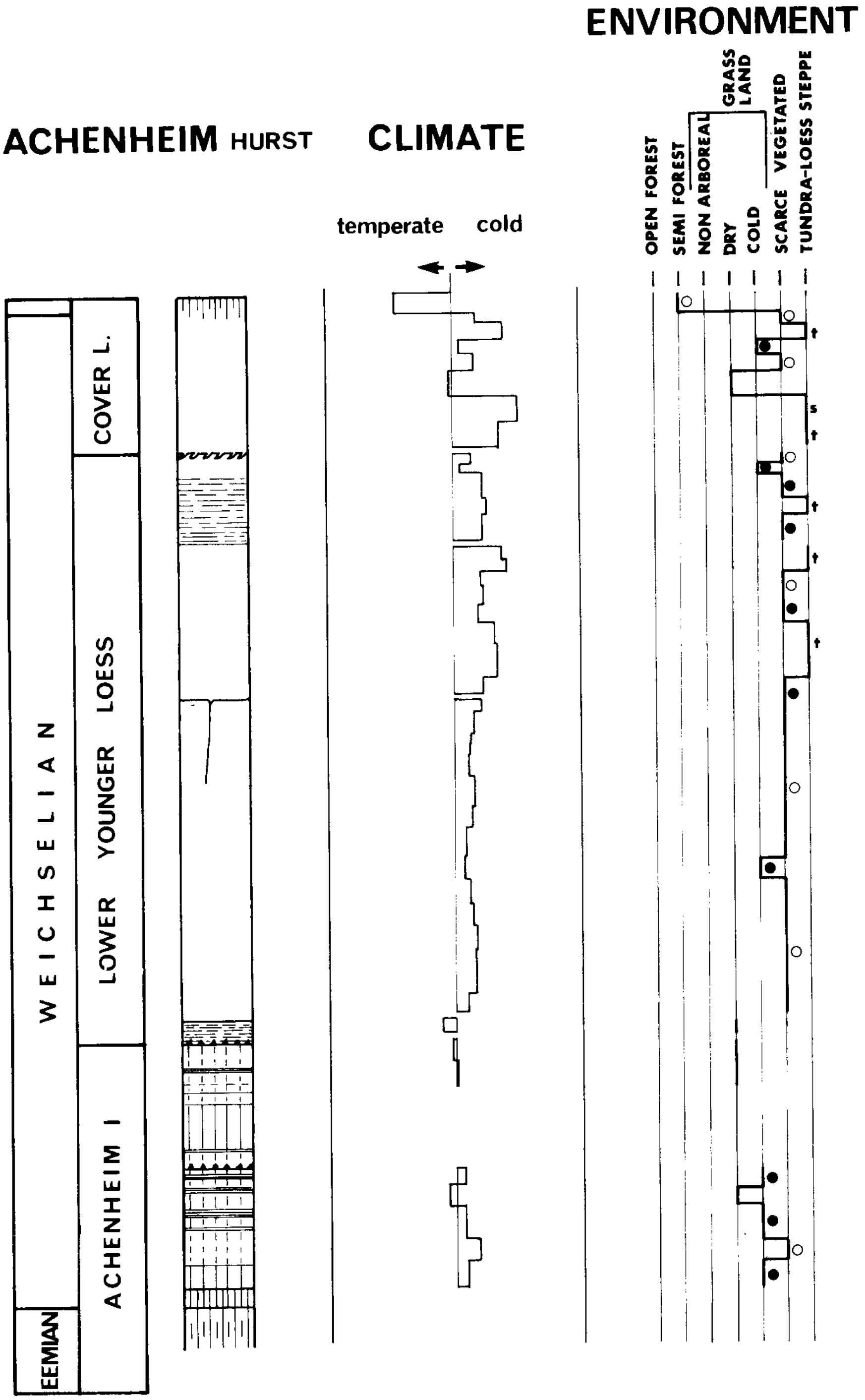

Fig.13. Younger Loess sequence (same legend as Fig.9).

et al., 1986), reveal an impoverishment of the fauna both in richness and in strength. It seems that unfavourable environmental conditions affected the malacological faunas blooming during this interval. In fact the species represented have a high ecological value: they can live and grow up under relatively various conditions (Rousseau, 1985, 1986). These drastic conditions would have prohibited the representation of stenotopic species (of low ecological value) and would have limited the representation of eurytopic species.

Contrary to the Upper Older Loess, a priori this climatic-sedimentary sequence does not show any analogy with that of Central Europe: the malacological fauna does not reveal the succession as previously defined; on the other hand, stratigraphical marks such as the lack of the lower Pleniglacial in the Lower Younger Loess (Sommé et al., 1986) or the occurrence of the markline related to the "Kesselt" seem to advocate the assignment of the Younger Loess to the domain of Northwestern Europe (Lautridou and Sommé, 1981, 1985, 1986; Sommé et al., 1986).

Importance of Achenheim for the European Quaternary stratigraphy

The quality of the climatic events recorded at Achenheim makes this site a reference section for the Middle and the Upper Pleistocene of western Europe. The climatic variations as shown by the statistical analysis of the malacological associations are relatively precise. They permit to determine the least climatic oscillation and to quantify its relative intensity. On the other hand, supplementary data on the environment are not sufficient to reconstruct the climatic history of the site. However, in this study it was prefered to emphasize the biotope aspect; consequently the thermal differences inside each grouping of associations had to be homogenized. In other words, while interpreting the results of the malacofaunal analysis the estimation of paleotemperatures and the reconstruction of the paleoenvironments could not be dissociated. In this way the study of the Achenheim faunas gives new and important elements for the comprehension of the Pleistocene of western Europe. We were able to try to make comparisons with the climatic sequences of Cerveny kopec although a great care should be taken in this respect. However, the climatic variations as found in this site only correspond to reconstructed environmental successions from classical malacological analyses. They did not give any detail on temperature fluctuations (Fig.3). They only reflect rather general climatic tendencies, from which only some comparisons, cycle after cycle, can be deduced.

Glacial cycle B

At Cerveny kopec cycle B is not well preserved. However, if we examine the climatic stratigraphy of the Weichselian loess deposits around Prague and Brno (Kukla, 1975, 1977) (Fig.14), we observe that the maximum cooling appears at the end of the cycle (Figs.13 and 14), and that it is followed by a relatively sudden warming up. In the same way, the two sequences present a rather marked cooling after the Interglacial, although less important in Alsace.

Glacial cycle C (Figs.3 and 12)

From a climatic–sedimentary point of view, the sequence of the Upper Older Loess is similar to that of Central Europe. Generally, these two sequences reveal two warming optimums, then a transition phase, a marker, a warming up and finally a Pleniglacial of which the intensity is nearly homogeneous contrary to that of Cerveny kopec as it seems. This assertion is however very relative again because of the difficult interpretation in climatic terms of the environmental results of Cerveny kopec.

Glacial cycle D (Figs.3 and 11)

The two sequences have in common that they show a relatively similar simplicity despite some differences. At Achenheim, the optimum temperate conditions occur distinctly before the brown soil in the loamy levels. The terminal cooling has the same intensity as the

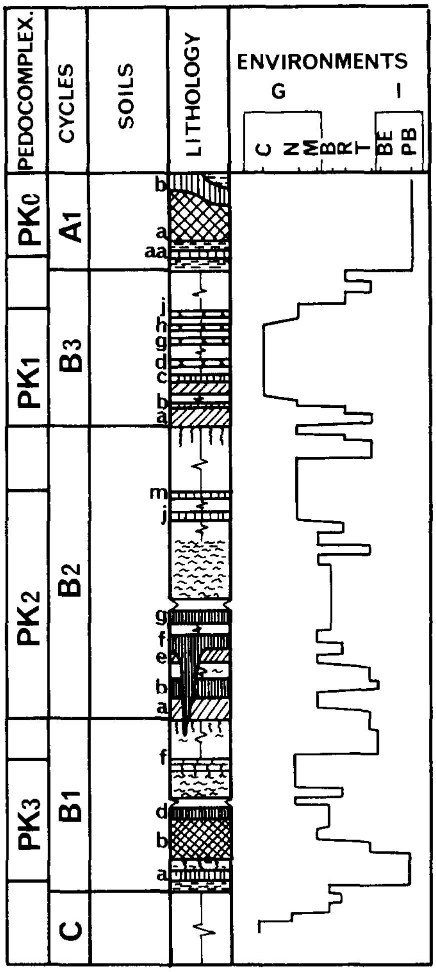

Fig.14. Lithostratigraphy of the Weichselian loess deposits around Brno (Czechoslovakia) (modified after Kukla, 1975, 1977) (same legend as Fig.3).

maximum coolings of cycle B at Achenheim. According to Kukla, at Cerveny kopec, it is the opposite. In the same way, in this sequence, a first important cooling is recorded after the Interglacial which has been observed in a tectonized section at Achenheim.

Glacial cycle E (Figs.3 and 10)

In this respect, the two sequences are completely different. At Achenheim, it is incomplete at the base. The recorded coolings are relatively minor and "monotonous", and this does not appear clearly from Cerveny kopec.

Glacial cycle F? (Figs.3 and 9)

The records obtained at Achenheim are fragmentary. The only common point between the two sites is that the maximum cooling is found at the half-sequence. Nevertheless, it is interesting to note the occurrence of *Columella columella* in the loessic sediments of this sequence as Kukla (1975) also observed *Columella columella* faunas in the loess F3 of Zidenice and Cerveny kopec.

If we compare the malacological associations of the glacial phases after cycles E and F, we notice a remarkable analogy between Achenheim and Cerveny kopec (Fig.15) — that is the real *Pupilla* associations are represented both in Alsace and in Czechoslovakia only once during glacial cycle D. These facts lead us to suggest that during cycles E and F, Central Europe and Alsace experienced different climatic and environmental conditions. With

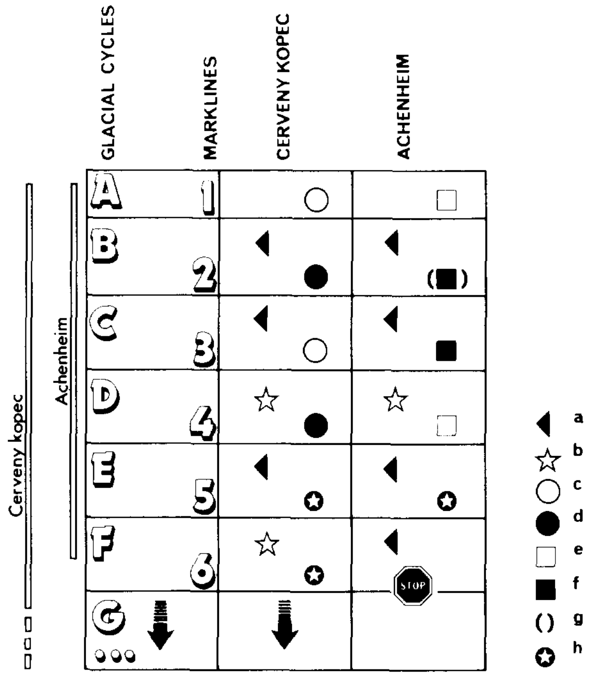

Fig.15. Comparison of the environmental changes between Cerveny kopec and Achenheim (after Kukla). *a* = *Columella columella* fauna; *b* = *Pupilla* fauna; *c* = *Helix* fauna; *d* = *Helicigona banatica* fauna; *e* = temperate grassland fauna; *f* = open forest fauna; *g* = data from pollen; *h* = unknown.

cycle D some analogies appear inducing to combine these two geographical domains, which is completely realized during cycle C. Finally, a new separation appears during the last cycle (B) when Alsace shows numerous affinities with Northwestern Europe (sensu Sommé et al., 1980).

Conclusions

The statistical analysis performed on the malacological faunas of Achenheim (Alsace) have permitted me to determine relatively precisely the climatic history of that site and of the region during the Middle and Late Pleistocene. Five climatic cycles have been proposed and correlated with glacial cycles B, C, D, E, F (Lautridou et al., 1986).

The lack of some levels in Alsace compared to the reference series of Central Europe, particularly those of Cerveny kopec, does not permit me to determine very precise relationships. Nevertheless, comparing these sites cycle after cycle, paleogeographical variations can be defined:

(A) During cycles F and E, Alsace and Central Europe did not belong to the same domain. The optimums of cycle F are indicated by the occurrence of *Columella columella* faunas at Achenheim, characteristic of a subarctic tundra environment. At Cerveny kopec, there are *Pupilla* associations, characteristic of a loess steppe environment, which thrived and grew up. During the following cycle, the pattern is reversed with a smaller cooling in Alsace (proto-loess steppe at Achenheim) and *Columella columella* associations at Cerveny kopec.

(B) During cycles D and C, the two domains are identical, particularly as regards a certain homogeneity of the Pleniglacials: *Pupilla* associations (cycle D) and *Columella columella* faunas (cycle C). Moreover, the sequence of cycle C is clearly similar to that of Central Europe.

(C) Cycle B shows a new, though not complete, separation between the two domains. The Achenheim sequence has specific characteristics common with both Northwestern Europe (marklines correlated, pedo-sedimentary assessment) and Central Europe (cooling optimums indicated by the occurrence of *Columella columella* associations).

In general, when considering the observations made at Achenheim and at Cerveny kopec, three major interpretations can be proposed.

(1) The interglacial faunas are always different. In Central Europe they can be characterized by the immigration of species from the southeast (Lozek, 1964b, 1969). In Western Europe and in Alsace, the interglacial faunas are similar to those living there today (Rousseau, 1986).

(2) The pleniglacial faunas of cycles F and E are different and indicate tundra or loess steppe environments.

(3) The pleniglacial faunas of cycles D, C and B seem similar and show similar life conditions in Alsace and Central Europe. Under these conditions, the cooling of cycle D must be considered as a major climatic event at the European scale as it suggests a generalized extension of the loess steppe in Western and Central Europe. However, to what does it correspond? In this respect, the faunal and palynological data are not informative enough as to permit some interpretation. For instance, to correlate this event with the minimum calculated insolation of Ruddiman and McIntyre (1976) seems for the moment inappropriate.

As a consequence, only the sequences of cycle C are really similar. Those of cycles D and B would correspond to a phase of generalization of the climatic conditions in Central Europe and Alsace, a condition completely realized during cycle C. Then during cycle B a contrast of climatic conditions appears between Central and of Northwestern Europe so that Alsace takes an intermediate position between the two, a status still held today by this region between the oceanic climate of western Europe and the more continental one of Central Europe. This was already noted for the interglacials.

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