A continent-wide framework for local and regional stratigraphies

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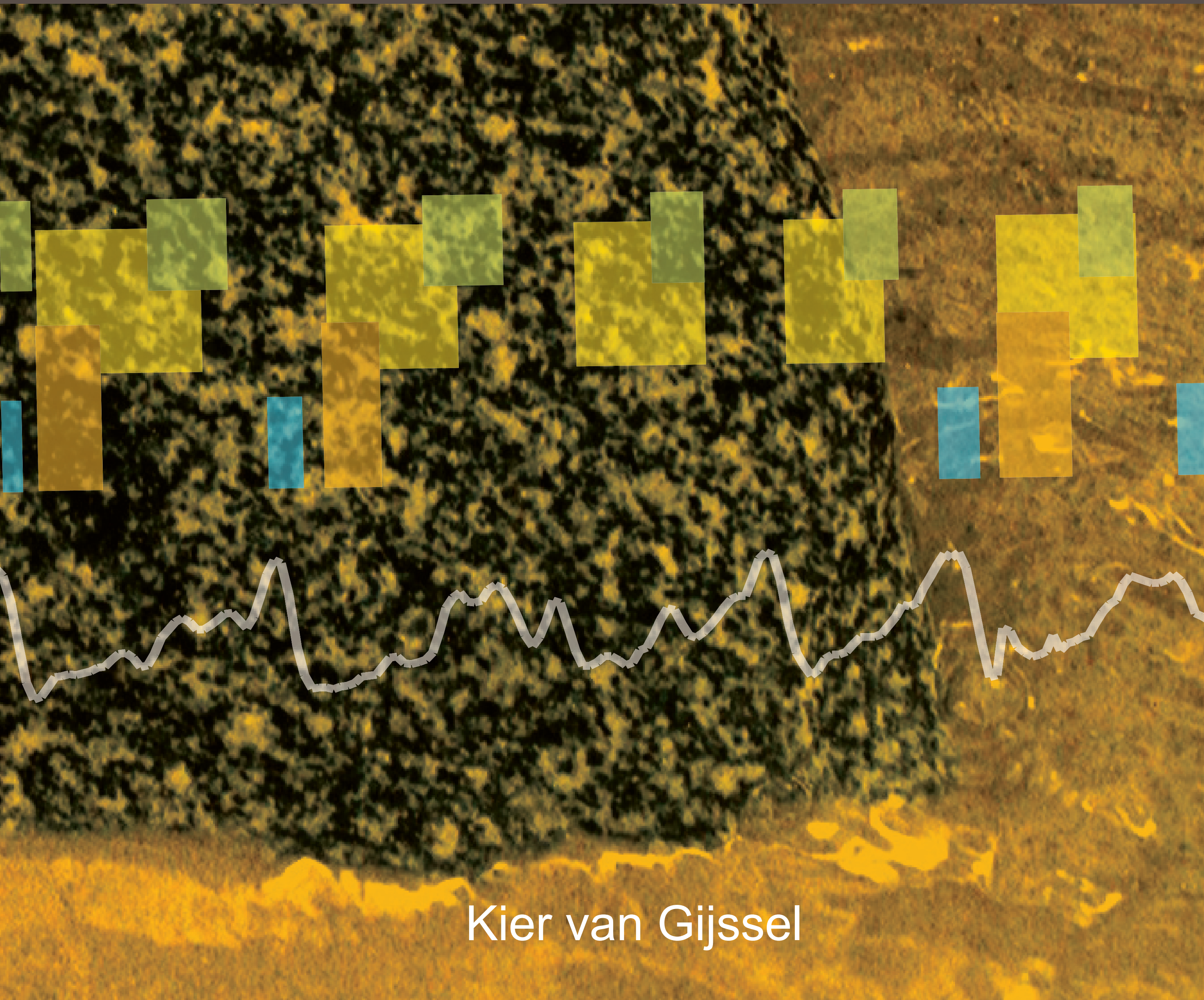
A continent-wide framework for local and regional stratigraphies:

application of genetic sequence and event stratigraphy to the Middle Pleistocene terrestrial succession of Northwest and Central Europe



Kier van Gijssel

A CONTINENT-WIDE FRAMEWORK FOR LOCAL AND REGIONAL STRATIGRAPHIES;

application of genetic sequence and event stratigraphy
to the Middle Pleistocene terrestrial succession
of Northwest and Central Europe

A CONTINENT-WIDE FRAMEWORK FOR LOCAL AND REGIONAL STRATIGRAPHIES;

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PROEFSCHRIFT

ter verkrijging van
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Kier van Gijssel

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in 1957

Promotiecommissie:

Promotores: Prof. Dr. J. W. M. Roebroeks
Prof. Dr. Th. van Kolfschoten

Referent: Prof. Dr. P.L. Gibbard (Cambridge)

Overige leden: Prof. Dr. H. Hooghiemstra (Amsterdam)
Prof. Dr. L.P. Louwe Kooijmans
Prof. Dr. J. van der Plicht
Prof. Dr. J.I. Svendsen (Bergen, Norway)
Prof. Dr. J. Vandenberghe (Amsterdam)

PREFACE / ACKNOWLEDGEMENTS

Some ten years ago I was given the opportunity to participate (as a graduate student) in the Pionier research programme 'Changing Views of Ice Age Foragers'[1], dealing with the Middle and Late Pleistocene human occupation of Europe. The Palaeolithic archaeological record of northern Europe dates well back into the Middle Pleistocene and from southern Europe we know claims for hominid presence of Early Pleistocene age. Roebroeks and Van Kolfschoten however, on the basis of significant differences in the context and quality of artefactual evidence combined with biostratigraphical evidence, stated in 1995 that there is no unambiguous proof of hominid occupation of Northwest and Central Europe prior to about 500 ka.
In order to give feedback on the time control over the scattered Palaeolithic evidence in the study area, as part of the terrestrial record, and to provide (geoscientific) arguments for the so-called 'short chronology'-hypothesis, the subject of my study within the scope of the project focused on the (chrono) stratigraphy of the local and regional Middle Pleistocene terrestrial sequence. I had to go into the difficulties and uncertainties associated with the traditional means of classification and dating of the Middle Pleistocene terrestrial record into inferred palaeoclimatic stages. This arduous task was compensated by the challenge to integrate multidisciplinary data from different type regions into a stratigraphical framework using sequence – and event stratigraphical principles. From these optimal matching is sought with the marine isotope stages (MIS), which at present is widely used as a global time-based reference frame.

I am indebted to all persons who in different ways have supported, encouraged and stimulated me during the past years when this work was 'under construction'.

Firstly, I wish to express my deep gratitude to Prof. Dr. J. W. M. (Wil) Roebroeks as much as to Prof. Dr. M. (Thijs) van Kolfschoten, who supervised the research project. They gave me, as a Quaternary geologist/- stratigrapher, the opportunity to contribute to the integration of (large-scale) geological and (site-oriented) archaeological perspectives. I had the privilege to share their enthusiasm and dedication in seeking a time frame for the Lower and Middle Palaeolithic sites and in finding objective proof for their 'short chronology' theory. Their great interest in all phases of the work, their many suggestions and critical remarks during the writing of the manuscript have been decisive for its realization.

Much support, response and fun was obtained from colleagues cooperating in the research project for which I thank: Jan Kolen, Dimitri De Loecker, Alexander Verpoorte, David van Reijbroeck, Hans Kamermans, Eelco Rensink, Barbara Speleers, Raymond Corbey and last but not least Olga Yates, our ever obliging secretary. Boudewijn Voormolen is thanked for his assistance in the field.

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I am also obliged to former colleagues, and still friends, of the Laboratory of Physical Geography and Soil Science of the University of Amsterdam: Dr. F.M. (Dick) van der Wateren, Dr. M. (Martin) Rappol, Dr. S.J. (Sjoerd) Kluiving and Dr. J.J.M. (Jaap) van der Meer as well as to those from the National Geological Survey (NITG-TNO): Dr. E.F.M. (Ed) de Mulder, Dr. A.F.B. (Ton) Wildenborg, Drs. P.C. (Peter) Vos, Dr. M.W. (Meindert) van den Berg and T. (Ton) Meijer.

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My parents, brothers and sister are thanked for maintaining family ties, which gave me a basis and background on which I could always rely. Facilities and accommodation supplied by the families Hanewald, Huijzer and Hachmang are appreciated.

Finally, I would like to thank my wife Maud for her patience and understanding. Finishing this thesis, home life and the raising of our children Onno and Noortje proved to be an uneasy combination in the last years. Nevertheless, I had to give time to this work. From now on I can spare more time for the three of them. My backpack will not be filled with thesis documents anymore during the holidays.

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[1] *Subsidised by the Dutch Organization for Scientific Research (NWO).*

Contents

SUMMARY

Chapter 1: Scope and objectives

The subdivision of the Quaternary[1], the last 2.6 Million years of the geological history, is predominantly based on local geological data. From this information, litho- and biostratigraphical units (respectively *formations* and *biozones*) are compiled into local and regional stratigraphies. Because of the fragmentary and genetically diverse nature of the land-based Quaternary record, characterized by numerous hiatal breaks (unconformities), a lack of usable index fossils and few geochronometrical control points, interpretation of the chronological sequence from these units has, however, been proven very problematic[2]. Therefore climatic change has traditionally been used as the most suitable basis for the subdivision of the Quaternary strata and time. Nevertheless, a climatostratigraphical subdivision of the local and regional stratigraphies into interpreted glacials and interglacials for Europe has never been documented in a satisfactory way. Attempts to correlate local and regional climate-based units from one region to another have led to many discrepancies. Loess/palaeosol sequences in the non-glaciated areas in Central Europe show more climatic cycles than the glacial sequences in Northwest Europe and the Alps, implying that the latter are deficient.

Does the Quaternary terrestrial record lack a sound chronological framework, an apparent continuous sequence of climatic events has been recovered from the deep ocean record. Climatic cyclicity in the marine oxygen isotope record is largely driven by astronomical forcing, commonly known as the 'Milankovitch theory'. Subsequent calibration and tuning using the astronomical polarity time-scale has provided this record with an accurate high-resolution chronology valid for at least the last 5 million years. Its trends are at present used in many earth scientific disciplines as a global standard for the timing and patterning of palaeoclimatic and –environmental events. At least 11 major glaciation cycles are demonstrated in the last million years which makes clear that the classical European glacial models are only rough frames of which the frequency of glacial and interglacial stages is commonly underestimated.

Two questions then arise which have been the starting points (and likewise challenges) for this thesis:

1 *How to reduce the difficulties and uncertainties associated with the subdivision and dating of the Quaternary terrestrial record?*

2 *How to match the observations on the continent with the oceanic record?*

Main objectives for study then (***chapter 1***) have been to investigate alternative approaches, supplementary to the traditional climatostratigraphical procedure, and to look for classifications that better represent the continental Quaternary record and that potentially offer opportunities to match with the global oceanic record. Nevertheless, interpretation of climatic signature remains the basis for classification of the Pleistocene terrestrial succession. The depositional sequences do not represent climatic periods then, but comprise reflections of climate forcing of different origin, type and scale order which have to match in some way the oceanic isotope record and lie at least within the time ranges of the marine isotope stages. This thesis focuses on the refinement of the (chrono)stratigraphical positions of the Middle Pleistocene[3] depositional sequences in Northwest and Central Europe. They belong to the classical Northwest European palaeoclimatic stages, i.e. part of the Cromerian Stage and the Elsterian, Holsteinian and Saalian Stages.

Chapter 2: Quaternary stratigraphy and correlation: a multidisciplinary approach

In ***chapter 2*** the different stratigraphical procedures that are at present applied to Quaternary research are reviewed and discussed by making a distinction between material descriptive units, interpretative units and temporal units. A historical review summarizes the ways in which traditional concepts, definitions and terminology, with respect to the Quaternary *System/Period,* have changed in time with new insights, increasing data availability and the progressive development of research and dating techniques.

The availability of objective criteria and their potential for large-scale interpretation and correlation, both spatial and temporal, is considered by discussing the nature of the terrestrial record, the scale and resolution of research and the aims of subdivision, i.e. the reconstruction of a land-based sequence of past climate-driven geological and ecological events compatible with the ocean isotope chronostratigraphy. Three supplementary procedures, unconformity-bounded -, genetic sequence – and event stratigraphy, applicable for the reconstruction of large-scale stratigraphical frameworks are dealt with in more detail. In order to be able to compare terrestrial to marine sequences, a method is proposed in which three subsequent steps are included:

1 *Arrangement of an informal interregional stratigraphical framework in which local multidisciplinary data are integrated*

With respect to the fragmentary and complex nature of the Pleistocene terrestrial succession the use of unconformity-bounded stratigraphy, recognized as a formal procedure as in the International Stratigraphic Guide (Salvador *et al.* 1994), offers the best opportunities for this purpose. Unconformities are surfaces of erosion and subaerial exposure. Basic unconformity-bounded units comprising erosional breaks of regional significance are called *synthems*. In many cases they largely correspond to the existing regional formations. Just as most of the lithostratigraphical codes contain lithogenetic information, synthems also record the succession of depositional environments in the type regions, which by interpretation of the successive facies and intermediate breaks are divided into *genetic* or *depositional sequences*. Since the major hiatal breaks in the successions also contain genetic and causal origins (erosion or stable surface conditions with soil formation), they are the virtual counterparts of the intervening depositional stratigraphical units.

2 *Interpretation and recognition of palaeoclimatic and tectonic events and cycles within this framework and interpretation of their scale order*

Based on the genetic unconformity-bounded stratigraphical successions from the different type regions, a final interpretative procedure includes the reconstruction of an event stratigraphical framework. Interpreted geological and ecological events in this thesis not only refer to short-term catastrophic phenomena, like volcanic eruptions, but also include climate-driven events, tectonics or sea-level changes with 4th order frequencies of 0.1 - 0.5 Ma. The latter are responsible for widespread cyclicity in the sedimentary record. Sedimentary sequences are then interpreted as products of periodic depositional and erosional events that are related to ice-sheet expansions, periglacial loess depositional cycles, marine transgressions and, in second case, to biogenic productivity (e.g. forest vegetation optima), soil development and fluvial response and mode. The proposed procedure is in many ways similar to climatostratigraphy but instead a hierarchical subdivision of inferential units is used to refer to the spatial and temporal scale, depositional environment and nature of the palaeoclimatic event. Thus, sequences refer to different Fennoscandian (FS) glaciation cycles, Central European (CE) loess accumulation phases and North Sea (NS) marine transgressions or to (local-scale) forest vegetation occurrences in which at different time-scale cycles can be distinguished.

3 *Searching boundary levels and time ranges for the climate type events in the global Marine Isotope Stratigraphy*

Searching boundary levels for the terrestrial climate-driven signals in the Marine Isotope Stratigraphy provides, under certain conditions and assumptions, a supplementary basis for the (chrono-) stratigraphical subdivision of the terrestrial Pleistocene sequences and events. Despite the lack of geochronological control and beyond independent regional factors both loess and (Late Pleistocene) vegetational records, by trend matching, show good correspondence with the global scale climate proxy records of the oceans and the ice cores. They indicate their suitability for use as a global template onto which the fragmentary terrestrial record of Europe may be fitted. At least the large-scale terrestrial sedimentary units, although of different origin, and their interpreted climate-driven geological and ecological events can be fixed, indirectly, to particular time intervals within the marine isotope stages (MIS) of the oceanic record. Although the boundaries of the regional depositional sequences are time-transgressive, the relatively short deglaciations[4] in the marine isotope record may serve as (remote) boundary levels for extrapolation of their terrestrial equivalents.
The assumption is made that limits to the amplitude of regional climatic variation are set by global changes. Extreme events will be reflected in both the oceanic and terrestrial records. Nevertheless, conclusions drawn on the regional response to global climatic change should be confirmed by independent evidence and include corrections for neotectonics among others.

Chapter 3: Contemporary Middle Pleistocene terrestrial stratigraphy of Northwest and Central Europe: a complex of local stratigraphies and palaeoclimatic stages

An outline of the former and contemporary Middle Pleistocene stratigraphy of Northwest and Central Europe is given in ***chapter 3.***
Although there is generally little dispute about the relative position of the sedimentary sequences in the glaciated areas, interregional correlation of the local and regional sequences to unravel the course and duration of the Middle Pleistocene glaciations and their correspondence to the loess cycles has been problematic. Interregional correlation is hampered by inconsistent definitions of the climatic stages and the limitations of the formal stratigraphical procedures. Climatostratigraphical misinterpretations and (biostratigraphical) miscorrelations cannot be excluded. In order to avoid terminological confusion the use of the broad terms warm and cold climatic stages or periods[5] is preferred. Five categories of major depositional environments and their sedimentary products are addressed. The basic, material building blocks contributing in different ways to the local and regional stratigraphies are:

- Sediments generated in glacial depositional environments,
- Sediments generated in subaerial periglacial depositional environments of which loess deposits are the major component,
- Marine coastal and shallow sea sediments,
- Fluvial and deltaic sediments produced by the large river systems,
- Lacustrine and biogenic sediments.

Their depositional sequences or ‘high-rank’ lithostratigraphical units comprise the bulk of the Pleistocene successions in the type regions. They support a continent-wide, twofold subdivision into formerly glaciated areas and non-glaciated areas of which the glacial and periglacial aeolian sequences, respectively, structure the local stratigraphies. Their large-scale stratigraphical significance and climatic interpretation is assessed. Intermediate sediments deposited in lakes, mires and bogs, as well as secondary carbonates, such as travertine, or soil complexes, are distinguished as local (sub) synthems providing useful additional palaeo-information. Moreover, bio- and chronostratigraphical control on the various sequences is reviewed.

Chapter 4: A supplementary stratigraphical framework for Northwest and Central Europe on the basis of sequence and event stratigraphy

Application of the combined unconformity-bounded – and genetic stratigraphy, as a basis for large-scale correlation purposes, is discussed in ***chapter 4.*** A large-scale framework requires a material basis from the type localities and type regions with uniformly defined units for interpretation. The utility of the different sedimentary, erosional and pedological elements in building up regionally comparable stratigraphical sequences, based on superposition, correlation and dating, depends upon:

- Sedimentary units deposited by widespread events,
- Infrequent events which leave highly distinctive evidence in the sedimentary record, both depositional and erosional,
- Environments in which continuous or near-continuous sedimentation takes place over long time periods,
- Sediments or fossils appropriate for dating.

The genetic units from the localised key sequences within the type regions, each of limited duration, integrate the existing multidisciplinary (litho-, bio-, soil- and other stratigraphical) data that are recognised and defined on the basis of bounding unconformities. They are ordered and compared within natural type regions that on the basis of geotectonic, morphological and drainage characteristics can be distinguished. Examples of major type regions in Northwest and Central Europe are the Anglo-Dutch North Sea (AD/NS) sub-basin and the middle course section of the Rhine (MR). From these regional groupings two informal correlation schemes have been compiled: one for the glaciated areas in Northwest Europe and the other for extraglacial Central Europe.
Nomenclature for synthems and genetic sequences is informal and generally refers to type locality, dominant lithofacies assemblage and/or regionally known stratigraphical code. Regional examples

are the Drente-1 till synthem within the Fennoscandian (FS) Saalian glacial sequence and the Leubsdorf gravel terrace synthem belonging to the Middle Rhine MT2 sequence respectively.

Next, an overall low-resolution stratigraphical framework of climate – and (neo) tectonic-related events for the Middle Pleistocene has been compiled by arranging them into a relative chronology on the basis of superposition, correlation of unconformity-bounded - and biostratigraphical markers and independent dates. Nearest reference vegetational and loess/pedological proxy records occur at Lac du Bouchet in the Massif Central (MC) and Červený Kopec (CK) in Slovakia. Important chrono- and bio indicators for the Middle Pleistocene are:

- The Brunhes-Matuyama geomagnetic reversal that took place at about 780,000 years ago and is assumed to mark the lower boundary of the Middle Pleistocene (Richmond 1996).
- Volcanic ash layers, such as those that have been deposited periodically in the Eifel area from about 570,000 years ago.
- Evolutionary and climatically characteristic biomarkers, such as the *Mimomys-Arvicola* boundary for the early Middle Pleistocene, the occurrence of characteristic fresh-water molluscs (*Viviparus diluvianus*) and the latest appearance date of *Pterocarya* tree pollen in the first warm stage(s) of the late Middle Pleistocene.

Chapter 5: Key stratigraphical sequences for the Middle Pleistocene in Northwest and Central Europe: two case studies

An overall picture of the past terrestrial climate reconstruction puzzle has to be compiled from localised key sequences. Case studies in which the genetic- and event-stratigraphical principles have been applied concern two key stratigraphical sequences: those of Kärlich and Ariendorf in the Middle Rhine type area and of the Schöningen sections in the Subhercynic Basin type area. From field investigations and literature research so-called Wheeler diagrams of the local depositional conditions have been reconstructed, showing alternating depositional, non-depositional and erosional stages and relevant multidisciplinary evidence, from which indications for the climatic conditions and tectonic activity in time can be interpreted.

- The early Middle Pleistocene loess/palaeosol sequence of the Kärlich section is, together with the late Middle Pleistocene Ariendorf section, of great stratigraphical importance because of the intercalating tephra beds from East Eifel volcanism. Based on their mineralogical composition, six eruption phases are distinguished in the region which have been dated by K/Ar- and Ar/Ar methods. Both sections contain volcanic ash layers of the so-called Rieden eruption phase that occurred between 450,000 and 370,000 years ago. Their stratigraphical positions are within and above cold-stage subaerial and fluvial deposits (*Kärlich H I* synthem respectively *Leubsdorf gravel terrace* synthem). Characteristic volcanic minerals of this phase, dominated by pyroxenes, are also found in underlying warm- stage deposits (*Kärlich G V* subsynthem). These chrono- and event-stratigraphical data are then used for interregional correlation to the Anglo-Dutch North Sea sub-basin where interaction of pyroxene-containing Rhine sediments with glacial and marine sequences occurred. With the help of a correlation scheme, it is concluded that the Fennoscandian Elsterian glaciation and the North Sea Holsteinian marine transgression most likely took place during the Rieden eruption phase. Interregional correlations to the loess areas in Central Europe suggest the time equivalency of the loess deposition cycles of the Middle Rhine Kärlich F subaerial sequence and the lower part of the Middle Rhine Kärlich H subaerial sequence with the Central European loess cycles CK H and CK F. As is concluded in *chapter 6,* these cold periods correspond to MIS 16 (659-620 ka) and MIS 12 (478-423 ka) respectively.
- The Schöningen sections are located in a small-scale sedimentary basin in which fossil-rich lake and mire sequences were deposited following periodic salt-tectonically related subsidence. Although incomplete and not superposed, the sequences reveal two more late Middle Pleistocene warm-stage forest optima, Reinsdorf and Schöningen, intermediate of the FS Elsterian and Saalian glaciations and following the Holsteinian warm Stage. This makes it plausible that the Elsterian glaciation took place during MIS 12 (and the Saalian glaciation during MIS 6). Also in the loess/palaeosol stratigraphies of Central Europe three Bt-type soil complexes are identified for this ice-free period outside Scandinavia.

Chapter 6: Synthesis: correlation of the Northwest and Central European Middle Pleistocene terrestrial succession with the Marine Isotope Stratigraphy

Chapter 6 provides a synthesis that reviews the possibilities for refinement of the low resolution Middle Pleistocene terrestrial event stratigraphy, which are sought in comparison and matching with the deep-ocean record. Although the global records are only a general guide to local climatic environment and thus a relatively poor basis for correlation, only the trends, not the amplitudes, in the oceanic isotope record are used for correlation. This trend matching is undertaken at two scales, both spatial and temporal:

1 Matching of evidence of (4th order climato-cyclic) events of global significance that are interpreted from the widespread genetic unconformity-bounded units,

2 Matching of palaeoclimatic evidence preserved in small-scale sequences and soil complexes in order to bridge the gaps between two subsequent global-scale events. Correlations of local evidence should be done by following the post-depositional succession from a large-scale MIS-fixed basal unit or a dated level upwards.

The most pronounced δ^{18}O-maxima occurred during MIS 2, 6, 12 and 16. It is generally agreed upon that the Late Pleistocene Fennoscandian Weichselian, British Devensian and Alpine Würmian glaciation maxima correspond to MIS 2, which in the extraglacial areas coincides with the loess accumulations in cycle B. The North Sea Eemian sea-level maximum and continental warm-stage type forest vegetation largely correspond to MIS 5e. Also the correspondence of the Fennoscandian Saalian and Alpine youngest Rissian (III) glaciation maxima, time equivalent to the Central European loess cycle C, to MIS 6 is well accepted nowadays. Serious event-stratigraphical problems are encountered further back in the Middle Pleistocene. Conclusions on the event-stratigraphical positions of the widespread glacial and subaerial sequences are:

- The Fennoscandian Elsterian, British Anglian glaciation and the Central European loess cycle F occurred during MIS 12 (478-423 ka), followed by the North Sea Holsteinian marine transgression (MIS 11c),
- The Fennoscandian Donian glaciation and the Central European loess cycle H took place in MIS 16 (659-620 ka) which was possibly followed by a North Sea marine transgression in East Anglia.

Two boundary levels of the isotopic glacial cycles, stage boundaries as defined by the SPECMAP-group (1984), are then identified for refining the chronostratigraphical position of the large-scale terrestrial events in the Middle Pleistocene. Most suitable for such chrono-correlative purposes are the deglaciation phases in the marine oxygen isotope record for which the so-called terminations serve as worldwide average dates. Their time intervals coincide with particular sedimentary changes in the terrestrial sequences such as Kukla's 'marklines'[6] in the stacked loess sequences of Central Europe, lower bounding unconformities of coastal marine sequences in the North Sea margins and increasing tree pollen contents in (glacial) lake records. Similar to the lower boundary of the Holocene Series, formally defined at 10,000 ^{14}C BP but regionally dated within the deglaciation of MIS 2/1 between 18 and 6 ka BP, and of the Late Pleistocene Substage, arbitrarily defined at 128 ka (termination II) within the deglaciation phase of MIS 6/5 between 135 and 122 ka, at least two Middle Pleistocene lower boundary levels, valid for both the glaciated and non-glaciated areas in Europe, can be placed at relevant MIS transitions further back in the oceanic record:

1 The lower boundary of the *late Middle Pleistocene* corresponding to the deglaciation interval of MIS 12/11 for which a date of 423 ka (termination V) has graphically been interpolated. This boundary level represents the transition of the regional Elsterian (Sanian 2/Okian) cold - to the Holsteinian (Hoxnian/Mazovian/Likhvinian) warm Stage. Arguments for equating this transition to the boundary level at MIS12/11 are:
   - The dates of the Rieden phase East Eifel tephra beds at around 450-370 ka in the Middle Rhine type region, the occurrence of pyroxene-dominated deposits in this type area and in the Anglo-Dutch North Sea type area from MIS 13 (*ca*. 500,000 years ago) and the stratigraphical position of the Fennoscandian Elsterian glaciation maximum in the North Sea type area intermediate of pyroxene-containing fluvial deposits (*chapter 5*),
   - The last appearance datum (LAD) of *Pterocarya* pollen which is tentatively used as a biostratigraphical marker in the reference pollen record of the MC Lac du Bouchet maar lake and coinciding with the North Sea Holsteinian marine transgression during MIS 11c (*ca*. 400,000 years ago),
   - The occurrence of exceptionally deep incision phases in several river terrace systems that probably took place during MIS 12 pre-dating the maximum ice-sheet expansion of the Fennoscandian Elsterian glaciation.

2 A boundary level corresponding to the deglaciation of MIS 16/15 (substage c) for which termination VII at 620 ka is the midpoint. This boundary level subdivides the Cromerian part of the *early Middle Pleistocene* into a *part A* and a *part B*. Terrestrial evidence for such an event-stratigraphical boundary level within the early Middle Pleistocene succession only is well-documented in eastern Europe. Here the mid-latitude Fennoscandian Donian glaciation is contemporary with the Russian Plain (RP) Borisoglebsk loess cycle and Central European loess H cycle which correspond to the ð^{18}O-maximum of MIS 16. Extrapolation of the small mammal *Mimomys-Arvicola* boundary combined with regional marker beds and dates from East Eifel tephra layers, also justifies the application of the subdivision of the early Middle Pleistocene in Northwest Europe. The *Mimomys-Arvicola* boundary is found in the warm event corresponding to the second peak (substage a) of MIS 15.

After the assignment of the event-stratigraphical position of large-scale sequences the intermediate, most local, events are also attributed to the continent-wide MIS-fixed framework:

- The late Middle Pleistocene (MIS 11-6: 423-128 ka) includes three warm climatic stages for which the Lac du Bouchet pollen record, showing 7 forest vegetation climaxes during this time interval, serves as the reference record. The forest vegetation occurrences from the Holsteinian glacial lake sequences are equated to the MC Praclaux forest vegetation assemblage and attributed to MIS11c. The forest climax occurrences in the lake sequences of Pritzwalk in the North German North Sea (NG-NS) type area, of Reinsdorf in the Subhercynic Basin (SB) type area, of Bilshausen in the Thuringian Basin (TB) type area and of MR Kärlich-Seeufer can be assigned to MIS 9 (339-303 ka), as well as the terrace travertine sequence of TB Bilzingsleben II. The SB Schöningen warm-stage type forest vegetation is attributed to MIS 7.
- During part B of the early Middle Pleistocene (MIS 15-12: 620-423 ka) some very warm events have occurred, as is represented by several soil complexes in Central Europe that regionally contain rubified Bt's ('Braunlehm') of forest soils (Ville, Ferreto). The glacial lake sequences of Ferdynandov in the Polish Plain (PP) type area and of Muchkap in the Russian Plain (RP) type area comprise two forest vegetation climaxes indicating correspondence to the MIS 15 substages e and a. The time interval between the FS Donian and FS Elsterian glaciations possibly contains two sea-level maxima in the AD-NS type area: one occurring during MIS 13 (Noordbergum and Ostend) and the other possibly occurring during MIS 15 (substage a): West Runton.
- Part A of the early Middle Pleistocene (MIS 19-16: 780-620 ka) lacks clear warm-stage palaeoclimatic signals of the 4th order.

Finally, the event-stratigraphical positions of the some Palaeolithic sites is integrated into the framework. Conclusions, which can be drawn on the early occupation of Northwest and Central Europe, are:

- There is so far no sound evidence of early human occupation before MIS 16, i.e. before *ca*. 600,000 years ago (see *Epilogue* on the Pakefield site),
- The event-stratigraphical position of the oldest early Middle Pleistocene sites, located in western Europe along the coasts and in the river systems draining chalk areas, give a maximum date from MIS 15 to 13 (between 620,000 and 480,000 years ago),
- Evidence for the first late Middle Pleistocene hominid presence, and coinciding with MIS 11, between 420,000 and 360,000 years ago, is only found in Britain (and northern France),
- The next occupation phase took place from south-eastern Europe and is dated in the second warm climatic optimum following the FS Elsterian/British Anglian glaciation: MIS 9, between 340,000 and 300,000 years ago,
- A final group of late Middle Pleistocene Palaeolithic sites can be attributed beyond doubt to MIS 7 and early MIS 6, between 250,000 and 160,000 years ago.

These conclusions largely confirm the so-called short chronology theory introduced by Roebroeks and Van Kolfschoten (1995). This theory involves the preassumption that on the basis of the found artefacts and settlement structures so far no occupation has occurred in northern Europe before 500,000 years ago, despite the claims of earlier dated hominid occupation. From the stratigraphical analysis in this thesis it is concluded that the lower boundary for the short chronology has to be set at about 600,000 years ago (= MIS 15).

[1] *When excluding the last 10,000 years of this time period, representing the Holocene Epoch/Series, the Quaternary Period/System consists of the complete Pleistocene Epoch/Series, wherefore these terms are broadly used as synonyms.*

[2] *At least beyond the limit of* ^{14}C *dating of about 40,000 to 50,000 years.*

[3] *Spanning the period from approximately 780,000 to 130,000 years ago.*

[4] *Deglaciations are characterized by the steep decrease of the* $ð^{18}O$ *ratio in the ocean waters as a result of rapid melting of ice-sheets, containing light* ^{16}O*-isotopes.*

[5] *Relative to present-day climate conditions.*

[6] *Boundaries between thick loess beds and palaeosol complexes based by a Bt-horizon.*

SAMENVATTING

Hoofdstuk 1: Inleiding

De stratigrafische indeling van het Kwartair[1], de laatste 2,6 miljoen jaar van de geologische geschiedenis, is voornamelijk gebaseerd op lokale geologische gegevens. De informatie uit deze gegevens is op lokaal en regionaal niveau in litho- en biostratigrafische eenheden onderverdeeld, waarbij de *formatie* respectievelijk de *biozone* de fundamentele eenheden zijn. De fragmentarische – en genetisch diverse aard van de terrestrische sedimentopeenvolging, het gebrek aan gidsfossielen en de ontoereikende dateringsmethoden vormen een groot probleem voor een gedetailleerde tijdsstratigrafische indeling van het Kwartair[2]. Traditioneel worden daarom de heersende klimaatcondities ten tijde van de afzetting geïnterpreteerd en ingedeeld in zogenaamde glaciale en interglaciale perioden. Zo zijn in Europa vele lokale en regionale indelingen opgesteld van relatief koude en warme perioden die refereren aan grootschalige klimaatveranderingen in het Pleistocene verleden. Interregionale correlaties van deze klimaatstratigrafische eenheden vertonen niettemin veel discrepanties en leiden (nog steeds) tot veel discussie met betrekking tot de plaatsing in de tijd. Zo komen er in de löss/paleosol stratigrafie van de niet-vergletsjerde gebieden in Midden-Europa bijvoorbeeld meer klimaatcycli voor als in de glaciale stratigrafieën van Noordwest-Europa en de Alpen.

Ontbreekt een degelijk chronologisch raamwerk op land, een schijnbaar volledige registratie van de Kwartaire klimaatgeschiedenis kan worden afgeleid uit de sedimentopeenvolgingen van de oceaanbodem. De klimaatcycli in de oceanische zuurstofisotopencurve zijn grotendeels door astronomische processen gestuurd, algemeen bekend als de 'Milankovitch theorie'. Voortdurende ijking en afstemming met hoge resolutie astronomische – en polariteittijdsschalen heeft de mariene zuurstofisotopenstratigrafie voorzien van een consequente chronologie voor de laatste 5 miljoen jaar. De trends worden tegenwoordig algemeen gebruikt als een wereldwijde standaard voor het reconstrueren van lokale – en regionale paleoklimaat- en –milieucondities in tijd en ruimte. Tenminste 11 glaciale cycli zijn aangetoond in de laatste miljoen jaar, hetgeen duidelijk maakt dat de klassieke glaciale modellen voor Europa slechts ruwe raamwerken zijn, waarin de frequentie van de glaciale en interglaciale perioden in het algemeen is onderschat.

Bovenstaande schets met betrekking tot de Kwartaire (chrono)stratigrafie vormde de aanleiding tot twee vragen die centraal staan in dit promotieonderzoek:

1 *Hoe zijn de moeilijkheden en onzekerheden van de terrestrische chronostratigrafische indelingen te verkleinen?*
2 *Hoe zijn de continentale en mariene stratigrafieën met elkaar overeen te stemmen en te correleren?*

Deze vragen (***hoofdstuk 1***) zijn de aanleiding geweest om naar alternatieve methoden naast de bestaande klimaatstratigrafie te zoeken en om aanvullende classificaties te vinden die de Kwartaire successie beter representeren en die mogelijkheden bieden voor correlatie met de mariene isotopenstadia. De interpretatie van klimaatcondities blijft niettemin de basis van de indeling van de Pleistocene successie. De afzettingen vertegenwoordigen echter geen klimaatperioden meer, maar paleoklimatologisch gestuurde gebeurtenissen van diverse aard, intensiteit en (schaal)omvang die op de een of andere manier in het globale tijdskader van de zuurstofisotopenstratigrafie passen en binnen de marges van de mariene isotopenstadia vallen. Dit proefschrift concentreert zich met name op de verfijning van de (chrono)stratigrafische posities van de diverse afzettingen uit het Midden-Pleistoceen[3] in Noordwest en Midden-Europa. Zij maken deel uit van de klassieke Noordwest Europese indeling in klimaatperioden, i.e. van het jongste deel van het Cromerien, het Elsterien, het Holsteinien en het Saalien.

Hoofdstuk 2: Kwartaire terrestrische stratigrafie en correlatie: een multidisciplinaire benadering

In ***hoofdstuk 2*** worden de verschillende stratigrafische methoden en technieken besproken die tegenwoordig in het Kwartaire onderzoek worden toegepast. Een onderscheid wordt gemaakt in materiaalbeschrijvende eenheden, interpretatieve eenheden en tijdseenheden. In een historisch overzicht wordt toegelicht hoe (traditionele) concepten, definities en terminologie betreffende het Kwartaire *Systeem/Tijdperk* zijn veranderd in de loop der tijd door nieuwe inzichten, de toenemende beschikbaarheid van gegevens en de voortschrijdende ontwikkelingen in onderzoeks- en dateringstechnieken.

Vervolgens wordt de classificatie en interpretatie van klimaatbepaalde afzettingen vanuit een ander, globaal gezichtspunt geëvalueerd. De beschikbaarheid van objectieve criteria en hun mogelijkheden voor grootschalige interpretatie en correlatie van stratigrafische eenheden in tijd en ruimte zijn beschouwd in relatie tot het karakter van de Kwartaire sedimentopeenvolging, de schaal en resolutie van onderzoek en het doel van de stratigrafische indeling, dat wil zeggen het reconstrueren van een klimaatgeschiedenis op land in overeenstemming met de mariene isotopenstratigrafie. De toepassingsmogelijkheden van diverse (alternatieve) stratigrafische methoden die geschikt zijn voor grootschalige indelingen en correlaties, zoals de interdiscordantie-, de sequentie- en de 'event'stratigrafie, zijn nader toegelicht. De werkwijze om tot een (objectieve) vergelijking van de terrestrische stratigrafische indelingen en de mariene isotopische stratigrafie te komen bestaat uit drie opeenvolgende onderdelen:

1 Het opstellen van een informeel, interregionaal stratigrafisch raamwerk voor het Midden-Pleistoceen, waarin de lokale interdisciplinaire gegevens zijn geïntegreerd

Gezien het fragmentarische en complexe karakter van de Pleistocene sequenties biedt de stratigrafische indeling op basis van regionaal significante discontinuïteiten of discordanties ('unconformities') als formele stratigrafische procedure, naast de litho-, bio- en chronostratigrafie en conform de 'International Stratigraphic Guide' (Salvador *et al.* 1994), de beste mogelijkheden. Afzettingen die begrensd worden door over grote afstanden te vervolgen discordanties zijn met de term *interdiscordante eenheden* of *synthems* te definiëren. Zij komen in veel gevallen overeen met de bestaande regionale formaties en beschrijven daarnaast lithofacies - en biofacieseigenschappen. Deze verwijzen naar bepaalde afzettingsmilieus, zoals bijvoorbeeld glaciale, mariene of fluviatiele afzettingsmilieus, en kunnen op grond hiervan geïnterpreteerd en ingedeeld worden als *genetische sequenties* of *'(genetic) depositional sequences'*. De discordanties zelf bevatten informatie over perioden met erosie of perioden met stabiele oppervlaktecondities, waarin meestal bodemvorming optrad.

2 Het interpreteren en vaststellen van klimaatgestuurde – en tektonische gebeurtenissen ('events') en cycli binnen dit raamwerk en de interpretatie van hun schaalgrootte

In deze interpretatieve fase worden de interdiscordante, genetisch-stratigrafisch ingedeelde sequenties in de verschillende regio's geassocieerd met diverse geologische en ecologische gebeurtenissen of 'events'. Niet alleen korte termijn catastrofale natuurverschijnselen, zoals vulkanische uitbarstingen, vallen hier onder deze term, maar ook langere termijn klimaatgestuurde processen, zeespiegelveranderingen en tektonische processen met een (vierde orde) frequentie tussen de 100.000 en 500.000 jaar. Deze zijn verantwoordelijk voor wijdverbreide cycliciteit in de Pleistocene sedimentopeenvolgingen. De genetische sequenties worden geïnterpreteerd als producten van periodieke afzettings- en erosieprocessen die gerelateerd worden aan ijskapuitbreidingen (glaciaties), lössafzettingscycli in periglaciale woestijnen, mariene transgressies, en in tweede instantie aan biogene productiviteit, bodemvorming en aggradatie- en insnijdingsfasen van rivieren. Deze procedure is in veel opzichten vergelijkbaar met de traditionele klimaatstratigrafie, met dit verschil dat voor de klimaatinterpretatie en de correlatie een hiërarchische indeling van 'events' wordt gebruikt die verwijst naar de ruimtelijke en temporele schaal, het afzettingsmilieu en de aard ervan. Ook de bijbehorende terminologie verwijst hiernaar: zo worden verschillende Fennoscandische (FS) glaciaties, Midden-Europese (CE) lössafzettingsfasen, Noordzee (NS) mariene transgressies en lokale loofbosvegetatievoorkomens onderscheiden.

3 Het zoeken naar grensniveaus en tijdsintervallen voor de terrestrische 'events' in de globale mariene isotopenstratigrafie

Vergelijking van de terrestrische klimaatbepaalde 'events' met de mariene isotopenstratigrafie kan onder bepaalde voorwaarden en aannamen een aanvullende basis voor de chronostratigrafische indeling van de Pleistocene successie vormen. Ondanks de beperkte geochronologische controle is, door 'trend matching', een goede overeenstemming aangetoond voor onder andere löss-sequenties en (Laat-Pleistocene) vegetatiesequenties met de isotopische oceaan- en landijskernregistraties. Zij geven aan dat de mariene isotopenstratigrafie als een sjabloon gebruikt kan worden, waarbij op indirecte wijze in ieder geval de grootschalige Midden-Pleistocene terrestrische eenheden en hun afgeleide klimaatgebeurtenissen, alsook de tijdshiaten, binnen de tijdsintervallen van de mariene zuurstofisotopenperioden ('marine isotope stages': MIS) geplaatst kunnen worden. In tweede instantie worden lokaal vastgestelde 'events', meestal uit een warme klimaatperiode, ingedeeld. Hoewel isochrone tijdsgrenzen ontbreken kunnen met name de relatief kortdurende deglaciaties[4] in de isotopenstratigrafie als grensniveaus dienen voor hun terrestrische equivalenten. Hierbij is de aanname gemaakt dat amplitudes in intensiteit en omvang door de globale klimaatveranderingen zijn gestuurd en dat extreme klimaatgebeurtenissen terug te vinden zijn in zowel de lokale als de globale genetische sequenties. Niettemin zullen conclusies die gemaakt zijn over de lokale en regionale respons van globale klimaatveranderingen altijd bevestigd moeten zijn door onafhankelijke aanduidingen/bewijzen en, indien van belang, correcties voor bijvoorbeeld tektonische activiteit moeten inhouden.

Hoofdstuk 3: Hedendaagse Midden-Pleistocene terrestrische stratigrafie van Noordwest- en Midden-Europa: een complex van lokale stratigrafieën en paleoklimatologische perioden

Hoofdstuk 3 geeft een historisch en hedendaags overzicht van de stratigrafische indelingen voor het Midden-Pleistoceen, zoals die in Noordwest - en Midden-Europa in de praktijk toegepast zijn en worden. Ondanks dat er weinig discussie over de relatieve positie van de verspreide genetische sequenties bestaat, zijn de vele lokale indelingen niet goed met elkaar overeen te stemmen om zo het klimaatverloop goed te kunnen reconstrueren. Interregionale correlaties worden onder andere belemmerd door de vaak onduidelijke definiëring van de klimaatfasen, de glacialen en de interglacialen, en door de beperkte mogelijkheden van de formele stratigrafische methoden. Hierdoor zijn klimaatstratigrafische 'misinterpretaties' en (bio)stratigrafische 'miscorrelaties' niet uit te sluiten. Om terminologische verwarring te voorkomen wordt de voorkeur aan de algemene termen koude en warme perioden[5] gegeven. Vijf categorieën van afzettingsmilieus en hun representatieve afzettingen worden in dit hoofdstuk nader besproken. De fundamentele, materiële bouwstenen die op diverse manieren bijdragen aan de lokale en regionale stratigrafieën zijn:

- sedimenten afgezet onder glaciale omstandigheden,
- sedimenten afgezet onder subaerische (periglaciale) omstandigheden, met löss als belangrijkste component,
- sedimenten afgezet in mariene milieus,
- fluviatiele en deltaïsche sedimenten afgezet door grote riviersystemen,
- sedimenten afgezet in lacustriene en biogene milieus.

Deze lithogenetische of 'hogerangs' lithostratigrafische eenheden vormen het gros van de Pleistocene sedimentopeenvolgingen in de typegebieden. Een tweedeling kan worden gemaakt in de zogenaamde glaciale stratigrafieën in de vergletsjerde gebieden in Noord-Europa en de rivierterras/löss-stratigrafieën in de niet-vergletsjerde gebieden in Midden-Europa. Hun stratigrafische betekenis en (paleo)klimatologische interpretatie voor grootschalige reconstructies worden geëvalueerd. Intermediaire sedimenten die afgezet zijn in meren, vennen en venen, alsook secundaire carbonaten, zoals travertijn, en fossiele bodemcomplexen, zijn als lokale (sub)synthems te onderscheiden die waardevolle paleoinformatie verschaffen. Daarnaast komen de biostratigrafische gegevens en kenmerken van deze verschillende Midden-Pleistocene genetische sequenties aan de orde en worden de (geochronologische) ouderdomsbepalingen besproken die met behulp van verschillende dateringstechnieken zijn gemeten.

Hoofdstuk 4: Een supplementair stratigrafisch raamwerk voor Noordwest- en Midden-Europa op basis van sequentie- en 'event'stratigrafie

De toepassing van de gecombineerde interdiscordantie –, genetische- en 'event'stratigrafie als basis voor grootschalige correlatiedoeleinden wordt in ***hoofdstuk 4*** behandeld. Een grootschalig raamwerk behoeft een materiële basis vanuit de typelokaliteiten en de typeregio's met uniform gedefinieerde eenheden voor interpretatie. De bruikbaarheid van de verschillende sedimentaire, erosieve en bodemkundige elementen om als bouwsteen voor een dergelijke, aanvullende, stratigrafische indeling te dienen hangt af van het voorkomen van:

- sedimentaire eenheden afgezet door grootschalige gebeurtenissen,
- zeldzame gebeurtenissen die een hoog onderscheidende (gids)

laag vormen in de opeenvolging, zowel sedimentair als erosief,
- afzettingsmilieus waarin continue of bijna-continue sedimentatie plaatsvindt over lange perioden,
- afzettingen of fossielen die geschikt zijn om te dateren.

De genetische eenheden van de verspreide typelokaliteiten, elk van beperkte tijdsduur, integreren multidisciplinaire (litho-, bio-, bodem- en andere stratigrafische) gegevens die vastgesteld en gedefinieerd zijn op basis van hun discordanties. Ze zijn gerangschikt en vergeleken binnen natuurlijk begrensde geotektonische typegebieden in Noordwest- en Midden-Europa, zoals bijvoorbeeld het Anglo-Nederlandse Noordzeebekken (AD/NS) en het Midden-Rijngebied (MR). Van deze regionale indelingen zijn twee informele correlatieschema's gecompileerd: een voor de vergletsjerde gebieden in Noordwest-Europa en een voor de gebieden daarbuiten in Midden-Europa. De naamgeving van de synthems en genetische sequenties is informeel en verwijst in het algemeen naar de typelokaliteit, de dominante lithofacies assemblages en hun regionaal bekende stratigrafische code. Voorbeelden zijn de Drente-1 keileem synthem binnen de Fennoscandische (FS) glaciale sequentie uit het Saalien respectievelijk de Leubsdorf grindterras synthem behorend tot de Midden-Rijn Mittelterrasse 2 sequentie.

Door vervolgens de grootschalige klimaatbepaalde – en tektonische gebeurtenissen in de verschillende regionale typegebieden door middel van superpositie, correlatie van interdiscordante - en biostratigrafische gidslagen en fossielen, en onafhankelijke dateringen in een relatieve tijdsvolgorde te plaatsen, wordt een continentaal, lage-resolutie 'event' stratigrafisch raamwerk voor het Midden-Pleistoceen gecreëerd. De pollenopeenvolging van Lac du Bouchet in het Massif Central (MC) en de löss/paleosolopeenvolging van Červený Kopec (CK) in Slowakije zijn de belangrijkste referentielokaties voor correlatie. Belangrijke interregionaal toepasbare tijds- en bio-indicatoren voor het Midden-Pleistoceen zijn:
- paleomagnetische omkeringen: de Brunhes-Matuyama omkering vond ongeveer 780.000 jaar geleden plaats en markeert de ondergrens van het Midden-Pleistoceen (Richmond 1996),
- vulkanische aslagen, zoals die periodiek in en rond het Eifelgebied zijn afgezet vanaf ongeveer 570.000 jaar geleden,
- evolutie- en klimaatkenmerken van (gids)fossielen, zoals de *Mimomys-Arvicola*-grens voor het vroeg Midden-Pleistoceen en het voorkomen van kenmerkende zoetwatermollusken (*Viviparus diluvianus)* en het laatste voorkomen van *Pterocarya* boompollen in de eerste warme periode(n) van het laat Midden-Pleistoceen.

Hoofdstuk 5: Stratigrafische sleutelsecties voor het Midden-Pleistoceen in Noordwest- en Midden-Europa: twee 'case studies'

Een algeheel beeld van de (Midden-)Pleistocene klimaatreconstructiepuzzel moet worden samengesteld uit diverse, verspreid voorkomende type-lokaliteiten. In ***hoofdstuk 5*** is de supplementaire stratigrafische methode toegepast op een aantal geologische sleutelsecties voor het Midden-Pleistoceen: die van Kärlich en Ariendorf in het Midden-Rijngebied en van Schöningen in het Subhercynische Bekken (SB). Vanuit veldwaarnemigen en literatuuronderzoek zijn met behulp van zogenaamde Wheeler-diagrammen reconstructies van de lokale afzettingscondities gemaakt, waarin een afwisseling van sedimentatie-, non-depositie- en erosiefasen te zien is die, op basis van de relevante multidisciplinaire gegevens, indicaties voor klimaatcondities en tektonische activiteit in de tijd geven.

In Kärlich en Ariendorf komen subaerische lössopeenvolgingen voor liggend op rivierterrassen die stratigrafisch van groot belang zijn vanwege de tussenliggende vulkanische aslagen afkomstig uit het nabijgelegen Oost-Eifelgebied. Op grond van hun mineralogische samenstelling zijn zes eruptiefasen onderscheiden die met behulp van K/Ar- en Ar/Ar-methoden gedateerd zijn. De sedimentopeenvolging in Kärlich beslaat vrijwel het gehele vroeg Midden-Pleistoceen. Ariendorf sluit hierop aan met een opeenvolging van het laat Midden-Pleistoceen tot heden. In beide secties komen aslagen van de zogenaamde Rieden eruptiefase voor die gedateerd zijn tussen 450.000 en 370.000 jaar geleden. Zij worden in stratigrafische posities temidden van en boven subaerische en fluviatiele koude periode-afzettingen (*Kärlich H I* synthem respectievelijk *Leubsdorf grindterras* synthem) aangetroffen. De karakteristieke vulkanische mineralen van deze fase, gedomineerd door pyroxenen, zijn in Kärlich ook aanwezig in onderliggende afzettingen van een warme periode (*Kärlich G V* subsynthem). Deze chrono- en 'event'stratigrafische gegevens worden daarna gebruikt voor interregionale correlaties naar het Noordzeegebied waar interactie van de pyroxeenhoudende Rijn-afzettingen met glaciale en mariene sequenties plaatsvond. Met behulp van een correlatieschema wordt aannemelijk gemaakt dat de Fennoscandische Elsterien glaciatie en de Noordzee Holsteinien mariene transgressie hoogstwaarschijnlijk plaatsvonden ten tijde van de Rieden eruptiefase. Interregionale correlaties naar de lössgebieden in Centraal Europa maken aannemelijk dat de lössafzettingscyclus van de Midden-Rijn Kärlich F subaerische sequentie equivalent is aan de Centraal Europese löss cyclus CK H en dat het onderste deel van de Midden-Rijn Kärlich H subaerische sequentie equivalent is aan de Centraal Europese lössafzettingscyclus CK F. Zoals in *hoofdstuk* 6 wordt geconcludeerd komen deze koude perioden respectievelijk met MIS 16 (659-620 ka) en MIS 12 (478-423 ka) overeen.

De geologische secties van Schöningen zijn gelegen in een kleinschalig sedimentatiebekken waar in samenhang met periodieke zouttektonische bodemdaling verschillende fossielrijke lacustriene sequenties zijn afgezet. Hoewel onvolledig en niet in superpositie tonen zij aan dat er tussen de Fennoscandische Elsterien en Saalien glaciaties nog twee warme fasen met loofbosvegetaties, respectievelijk Reinsdorf en Schöningen, volgend op de Holsteinien warme periode voorkomen. Dit maakt het aannemelijk dat de Fennoscandische Elsterien landijsuitbreiding plaatsvond in MIS 12 (en de FS Saalien glaciatie in MIS 6), zoals ook in de löss-stratigrafie van Midden Europa drie Bt-type bodemcomplexen te herkennen zijn voor deze landijsvrije periode buiten Scandinavië.

Hoofdstuk 6: Synthese: correlatie van de Noordwest- en Midden-Europese Midden-Pleistocene successie met de mariene isotopenstratigrafie

In ***hoofdstuk 6*** worden als synthese de 'event'stratigrafische posities van de lokaal en regionaal vastgestelde klimaatbepaalde geologische en ecologische reflecties vergeleken en in overeenstemming gebracht met de tijdsintervallen uit de zuurstofisotopenstratigrafie van de oceanen. Omdat de isotopencurve slechts een algemene leidraad voor de correlatie van glaciaties en deglaciaties is zijn alleen de trends, niet de amplitudes, voor correlatie gebruikt. Deze 'trend matching' wordt op twee schaalniveaus uitgevoerd:
1 in eerste instantie worden de grootschalige (vierde orde klimaatcyclische) 'events', afgeleid van wijdverbreide genetische sequenties, gekoppeld aan de mariene isotopenstadia,

2 daarna worden de paleoklimatologische 'events' geïnterpreteerd uit lokale, niet-glaciale sequenties en bodemcomplexen binnen dit raamwerk ingevuld, bij voorkeur vanaf een MIS-gekoppelde stratigrafische basis of een gedateerd niveau omhoog, om zo de hiaten te overbruggen.

Globaal gezien zijn MIS 2, 6, 12 en 16 de meest uitgesproken koude isotopenfasen. Aanwijzingen vanuit de goed gedocumenteerde Laat-Pleistocene landstratigrafie geven aan dat de 'event'stratigrafische positie van de Fennoscandische Weichselien – , de Britse Devensian en de Alpiene Würmien glaciaties overeenkomen met MIS 2 en die van de Noordzee Eemien mariene transgressie en de lokale Eemien bosvegetatiemaxima overeenkomen met MIS 5e. Ook de overeenstemming van de Fennoscandische Saalien- en de laatste Alpiene Rissien (III) landijsuitbreidingen met MIS 6 (185-128 ka), tijdsequivalent aan de Midden-Europese lössafzetting in cyclus C, is tegenwoordig algemeen geaccepteerd. Serieuze problemen doen zich voor met betrekking tot de 'event'stratigrafische posities van de Fennoscandische Elsterien en Donien glaciaties.

Conclusies met betrekking tot de 'event'stratigrafische posities van de wijdverbreide glaciale en subaerische sequenties zijn dat:
- de Fennoscandische Elsterien -, de Britse Anglian glaciatie en de Midden-Europese lössdepositie in cyclus F plaatsvonden gedurende MIS 12 (478-423 ka), gevolgd door de Noordzee Holsteinien mariene transgressie (MIS 11c),
- de Fennoscandische Donien glaciatie en de Midden-Europese lössdepositie in cyclus H optraden in MIS 16 (659-620 ka) en mogelijk gevolgd worden door een Noordzee mariene transgressie in East Anglia.

Vervolgens worden twee grensniveaus van isotopische glaciale cycli, stadiagrenzen *cf.* SPECMAP-groep (1984), gebruikt voor een verfijning van de chronostratigrafische positie van de grootschalige terrestrische 'events' in het Midden-Pleistoceen. Het meest geschikt hiervoor zijn de deglaciatiefasen uit de mariene isotopenstratigrafie, waarvoor de zogenaamde terminaties als, grafisch geïnterpoleerde, wereldwijde dateringsgemiddelden gelden. Gedurende de deglaciatiefasen treden ook op land ingrijpende klimatologische veranderingen op die in een aantal duidelijke grensniveaus weerspiegeld zijn, zoals Kukla's 'marklines'[6], ondergrenzen van mariene transgressies en de snelle toename van bomenpollen in glaciale meerafzettingen. Zoals de ondergrenzen van het Holoceen (10.000 ^{14}C jaren BP) en het Laat-Pleistoceen goed overeenkomen met de arbitraire tijdsgrenzen voor de terminaties I (12,5 ka, als gemiddelde voor de deglaciatiefase van MIS 2/1 tussen 18 ka en 6 ka BP) en II (128 ka, als gemiddelde voor de deglaciatiefase van MIS 6/5 tussen 135 ka en 122 ka) worden nog twee oudere isotopische grensniveaus gebruikt en gelijkgesteld met terrestrische Midden-Pleistocene grensniveaus:

1 Een voor de overgang van het *vroeg* - naar het *laat Midden-Pleistoceen* gesteld op het wereldwijde gemiddelde van 423 ka (terminatie V) voor de deglaciatiefase van MIS 12 naar MIS 11. Dit niveau vertegenwoordigt de overgang van de regionale Elsterien (Sanien 2/Okien) koude periode naar de Holsteinien (Hoxnien/Mazovien/Likhvinien) warme periode. De bewijsvoering hiervoor wordt gegeven aan de hand van:
   - dateringen van Oost-Eifel vulkanische aslagen rond 450-370 ka (Rieden fase) in het Midden-Rijn typegebied, het veelvuldig voorkomen van pyroxenen in subaerische en fluviatiele afzettingen in dit typegebied en stroomafwaarts van de Rijn in het Anglo-Nederlandse Noordzee typegebied vanaf MIS 13, ca. 500.000 jaar geleden, alsmede de stratigrafische positie van het Fennoscandische Elsterien glaciatiemaximum intermediair van pyroxeenhoudende fluviatiele afzettingen (*hoofdstuk 5*),
   - het laatste voorkomen van *Pterocarya* pollen in de referentieopeenvolging van Lac du Bouchet in Zuidoost-Frankrijk en in de glaciale meerafzettingen in Noordwest Europa, welke gelijktijdig met de mariene Holsteinien transgressie in het Noordzeebekken plaatsvond gedurende MIS 11c, ca. 400.000 jaar geleden,
   - het voorkomen van grote erosiediscordanties in de terrasopeenvolgingen van vele riviersystemen die hoogstwaarschijnlijk plaatsvonden in MIS 12 voorafgaand aan de maximale landijsuitbreiding van de Fennoscandische Elsterglaciatie.

2 Een tijdsgrens voor een onderverdeling binnen het vroeg Midden-Pleistoceen in een deel A en een deel B en geplaatst op het wereldwijde gemiddelde van 620 ka (terminatie VII) voor de deglaciatiefase van MIS 16 naar MIS 15. De bewijzen voor een grensniveau overeenkomend met MIS 16/15 kunnen alleen in Oost-Europa goed onderbouwd worden. De Fennoscandische Donien landijsuitbreiding in dit gebied is tijdsequivalent aan de Borisoglebsk lösscyclus op de Russische Vlakte (RP) en aan de Midden-Europese löss H cyclus. Extrapolatie van de positie van de *Mimomys-Arvicola* grens, gecombineerd met regionale gidslagen en dateringen van Oost-Eifel vulkanische aslagen, rechtvaardigen ook het toepassen van dit grensniveau in Noordwest Europa. De *Mimomys-Arvicola* grens bevindt zich in de tweede piek (a) van de warme periode overeenkomend met MIS 15.

Na de bepaling van de 'event'stratigrafische positie van de grootschalige sequenties worden de intermediaire, meest lokale, warme tijd-gebeurtenissen in dit continentale, MIS-gekoppelde raamwerk geplaatst:
- Het laat Midden-Pleistoceen (MIS 11-6: 423-128 ka) omvat drie warme perioden, waarvoor de pollensequentie van Lac du Bouchet, die 7 subfasen met bosvegetatievoorkomens binnen deze warme perioden laat zien, als referentie dient. De bosvegetatieoptima uit de Holsteinien meerafzettingen zijn gelijktijdig met die van de MC Praclaux bosvegetatie-assemblage en overeenkomend met MIS 11c (423-ca. 400 ka). De bosvegetatievoorkomens van Pritzwalk in het Noordduitse Noordzee (NG-NS) typegebied, van Reinsdorf in het Subhercynische Bekken (SB), van Kärlich-Seeufer (MR) en Bilshausen in het Thüringer Bekken (TB) zijn in MIS 9 (339-303 ka) te plaatsen, evenals de travertijnvoorkomens in het rivierterras van Bilzingsleben II (TB). De Schöningen bosvegetatie (SB) is in het warme MIS 7 te plaatsen.
- In deel B van het vroeg Midden-Pleistoceen (MIS 15-12: 620-423 ka) komen een aantal zeer warme fasen voor, getuige het voorkomen van uitgesproken bodemcomplexen in verschillende typegebieden in Midden-Europa. Meerafzettingen met twee bosvegetatie-optima, overeenkomend met de subfasen e en a van MIS 15, komen voor in Ferdynandov in het Poolse Vlakte (PP) typegebied en in Muchkap in het Russische Vlakte (RP) typegebied. Mariene transgressies in het Anglo-Nederlandse Noordzee typegebied zijn opgetreden in MIS 13 (Noordbergum, Ostend) en mogelijk ook in MIS 15a (West-Runton).
- Deel A van het vroeg Midden-Pleistoceen (MIS 19-16: 780-620 ka) bevat weinig aanknopingspunten voor duidelijke warme klimaatgebeurtenissen.

Tot slot zijn de 'event'stratigrafische posities van een aantal Paleolithische vindplaatsen in het raamwerk geïntegreerd. Hieruit kunnen volgende conclusies met betrekking tot de vroegste bewoningsfasen in Noordwest – en Midden-Europa worden getrokken:
- tot op heden zijn er geen overtuigende bewijzen voor bewoning

voor MIS 16, dit is ca. 600.000 jaar geleden (zie naschrift over de Pakefield site),

- de ‘event’stratigrafische positie van de oudste vindplaatsen in het vroeg Midden-Pleistoceen, gelegen langs de kusten van de Krijtgebieden in West-Europa, komen overeen met MIS 15 tot en met MIS 13, tussen 600.000 – 480.000 jaar geleden,
- aanwijzingen voor de eerste menselijke bewoning in het laat Midden-Pleistoceen en tijdsequivalent aan MIS 11, tussen 420.000 – 360.000 jaar geleden, zijn alleen in Engeland (en Noord-Frankrijk) aangetroffen,
- een volgende bewoningsfase, vanuit het zuidoosten van Europa, volgt in de tweede warme periode met een bosvegetatie na de Fennoscandische Elsterien/Britse Anglian glaciatie: in MIS 9, tussen 340.000 – 300.000 jaar geleden,
- een laatste groep laat Midden-Pleistocene Paleolithische vindplaatsen kan zonder twijfel geplaatst worden in de warme periode overeenkomend met MIS 7 en het eerste deel van MIS 6, tussen 250.000 en 160.000 jaar geleden.

Deze conclusies ondersteunen goeddeels de zogenaamde ‘korte chronologie’-theorie, zoals door Roebroeks en van Kolfschoten in 1995 is geïntroduceerd. Deze theorie behelst dat noordelijk Europa, op grond van de tot nu toe gevonden artefacten en bewoningsstructuren, niet voor 500.000 jaar geleden bewoond is geweest, ondanks vele claims voor vroegere bewoning. Uit de stratigrafische analyse in dit proefschrift blijkt dat de ondergrens voor de ‘korte chronologie’ op maximaal 600.000 jaar (= MIS 15) moet worden gesteld.

[1] *Op de laatste 10.000 jaar na, het Holoceen, bestaat het Kwartair geheel uit het Pleistoceen. Beide termen worden daarom veelvuldig als synoniemen gebruikt.*

[2] *Dit geldt in ieder geval buiten de ^{14}C-dateringslimiet van ongeveer 40.000-50.000 jaar.*

[3] *De periode tussen ongeveer 780.000 jaar en 130.000 jaar geleden.*

[4] *De relatief korte perioden van een ^{18}O-isotopenmaximum naar een ^{18}O–minimum als gevolg van het snel smelten van de ijskappen.*

[5] *Relatief ten opzichte van de huidige klimaatcondities.*

[6] *Grenzen tussen dikke lösslagen en bodemcomplexen met aan de basis een Bt-type horizon.*

INTRODUCTION

1.1 Scope and objectives

Age and chronology are unifying themes in interdisciplinary studies on palaeoreconstructions of the terrestrial Quaternary[1] record. Its sediments, fossils and landforms contain the history of environments, climate, tectonic activity and human occupation of the last *c*. 2.6 Ma of the geological time scale[2]. Unfortunately, the complete pattern of palaeoenvironmental and palaeoclimatic change in time and space from the European continent is almost invariably poorly represented due to the highly fragmentary and genetically diverse nature of its record. Terrestrial Pleistocene stratigraphy and correlation is constrained by the predominance of (erosional) unconformities, a lack of usable index fossils and few geochronometric control points. These characteristics restrict to a large degree the availability of objective criteria for classification into natural, correlative units.

Moreover, the customary means of dating and correlation by dividing the local and regional stratigraphies of Europe into interpreted glacials and interglacials, necessarily based on multiple criteria, has never been documented in a satisfactory way. Attempts to correlate the climate-based units from one region to another have led to many discrepancies. Loess/palaeosol sequences in the non-glaciated areas show more climatic cycles than the glacial sequences in the Alps and in northern Europe, implying that the latter are deficient. Furthermore, most of the local Pleistocene stratigraphies are co-controlled by independent regional geographical, geological and (neo-)tectonic factors. For example, the fluvial terrace stratigraphies, closely linked with the loess stratigraphy of Central Europe, are complicated by (neo-)tectonic activity in these regions.

1. *How to reduce the difficulties and uncertainties associated with the subdivision and dating of the Pleistocene terrestrial record?*

> 'The ideal situation would be to find absolute age markers at all horizons in all environments, so that we could have a calendar of events divided into say 1000 years segments, giving complete correlation of sediments, processes and events over the earth's surface' (R.G. West 1968).

West's utopian situation became somewhat more realistic, when in the 1970s, the dating of the fluctuations in $^{18}O/^{16}O$ ratios from the shells of fossil foraminifera in ocean floor sediments[3] became an important stratigraphical tool. Technological and methodological advances in dating and subsequent calibration and tuning with astronomical - and polarity time scales since provided the marine isotope record an accurate high resolution chronology valid for the last 5 million years or beyond (Lourens *et al.* 1996). The development and present existence of the global chronostratigraphical time scale (*Fig. 1.1*) as a standard is crucial for the timing of palaeoclimatic and –environmental events, and a prerequisite for the refinement of the chronostratigraphy of the terrestrial Quaternary deposits, although the resolution might not be as high as West's 1000 years.

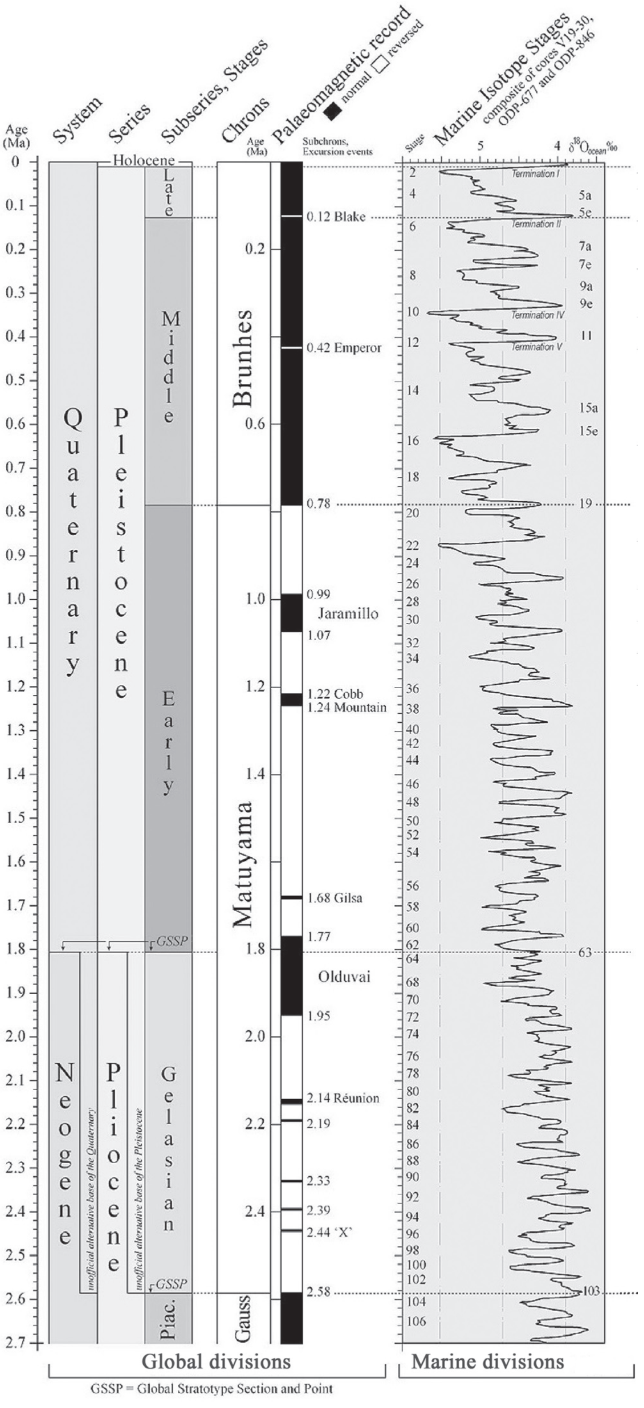

Figure 1.1 Global chronostratigraphical correlation table for the last 2.7 million years (Subcommission on Quaternary Stratigraphy, International Commission on Stratigraphy, Gibbard *et al.* 2004).

Within the overall context of an apparent continuous registration of the climatic history in the deep-ocean and ice-core records, the applicability of (conventional) climatostratigraphy to the terrestrial record is now seen as inadequate to interpret and reveal a relatively high-resolution sequence, in particular in the formerly glaciated areas. Nor does it resolve the problems of deficiencies and time-transgressive boundaries. The palaeoclimatic stages in many land-based stratigraphies are, in fact, not time stages but rather represent palaeoclimatic events of different origin, type and scale order. Unfortunately, the terrestrial stratigraphy can only indirectly be correlated with the oceanic record, because of the lack of chronological controls. Nevertheless, the classic glacial models are coarse structures, whilst the terrestrial climate-based stages and their associated depositional sequences have to match in some way the global template of the marine isotope and polarity stratigraphical frameworks. This offers opportunities for correlation with the wide-spread climate-driven sedimentary sequences in the glacial stratigraphy, in the loess/palaeosol stratigraphy, in the coastal marine stratigraphy as well as for correlation with local pollen records from suitable localities, for example, (‘postglacial’) lake sequences.

2. How do the observations on the continent match the oceanic record?

Both questions have been starting points (and likewise challenges) for this thesis. They initiated the need to search for an alternative approach, supplementary to the traditional climatostratigraphical procedure. Obviously climate is the only common denominator that can be used to compare the terrestrial and the marine sequences. Subsidiary, non-interpretive classifications are required that better represent the continental Pleistocene record and that potentially offer opportunities for large-scale time/space interpretations and eventually for correlation with the global oceanic record. One of the research objectives then has been the integration of multidisciplinary local data into an informal stratigraphical framework for Northwest and Central Europe using sequence – and event-stratigraphical criteria. Such an overall framework requires a material basis with uniformly defined units for interpretation. Moreover, the framework should be attended to an unambiguous nomenclature. Existing (and available), local datasets from several natural type regions in Northwest and Central Europe have for this purpose been gathered, reviewed and (re-)evaluated[4]. Stratigraphical units within the type regions are arranged on the basis of superposition, criteria of regional significance (e.g. bounding unconformities), correlation and independent dating. Then, interpretation of environmental facies changes arises for discussion in order to reconstruct regional sequences of events which can be associated with climatic cycles and (neo-) tectonic rearrangements of different magnitude and duration.
Using this framework, the intention of this thesis is to refine the (chrono)stratigraphical positions of the depositional sequences and unconformities associated with the classical Northwest European palaeoclimatic stages of the Middle Pleistocene[5], i.e. part of the Cromerian, the Elsterian, the Holsteinian and the Saalian stages. Their correlation with the loess/palaeosol cycles in Central Europe and the Alpine glacial stages is dealt with. Finally, optimal matching of the event-based continental stratigraphy for the Middle Pleistocene is sought with the marine isotope stages (MIS) of the ocean-core chronostratigraphy.

Comparable selective work on the relation and equation of terrestrial sequences to the global isotope scale has been dealt with by many other authors, including Kukla (1975, 1977, 1987), Turner (1975, 1996), Bowen (1978), Sibrava *et al*. (1986), Zubakov and Borzenkova (1991), Ehlers (1999), Gibbard and West (2000) and Vandenberghe (2000). The present thesis is another contribution to this issue, yet based upon a different approach, i.e. the application of genetic sequence[6] - and event-stratigraphical principles and attempting comprehensiveness by systematically comparing existing (Middle Pleistocene) evidence from different natural type regions in Northwest and Central Europe.
Within the scope of this research project this procedure is of great help in the improvement of time control over the scattered Palaeolithic evidence in the study area which, as another component of the terrestrial record, dates far back into the Middle Pleistocene (*Fig. 1.2*).

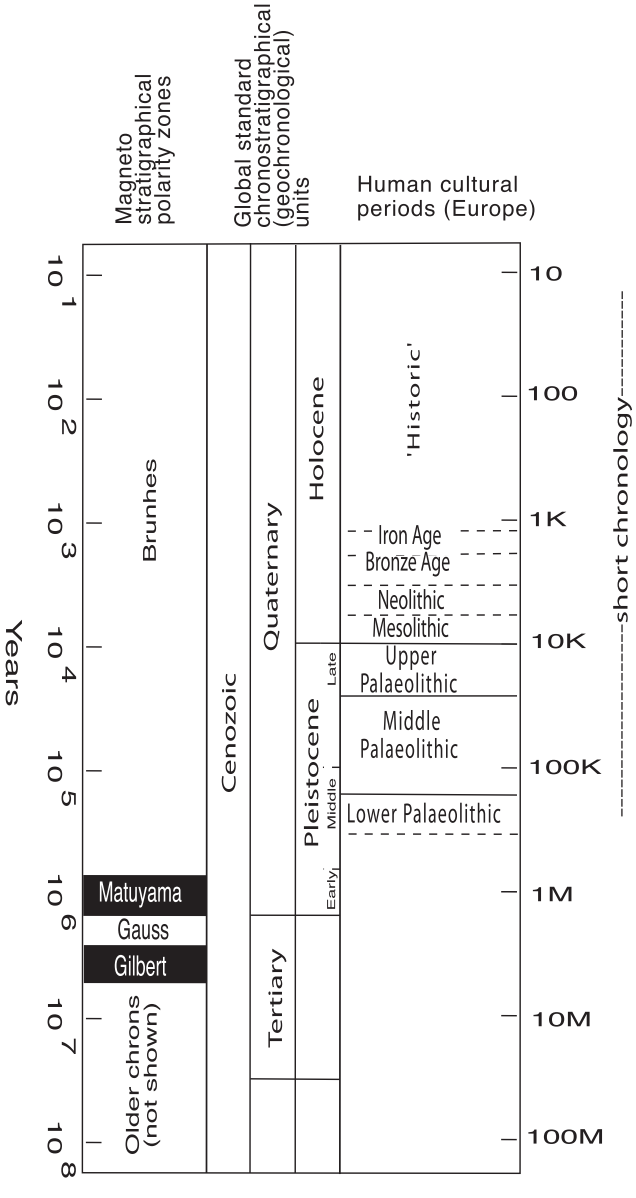

Figure 1.2 Comparison of archaeological and geological subdivision (modified after Stein and Linse 1993).

1.2 Outline of this thesis

Chapter 2 begins with an introduction to the main principles and methods concerning the Quaternary subdivision, chronology and terminology (*sections 2.1 and 2.2*). Before developing alternative concepts and starting supplementary stratigraphical procedures, the availability of objective criteria in the terrestrial geological succession and their suitability for large-scale interpretations is assessed in the *sections 2.3* up to *2.5*. Considerations of these prerequisites involve three basic issues:

- The nature of the terrestrial record,
- Scale and resolution of research, both spatial and temporal,
- Aims of subdivision, i.e. the reconstruction of a land-based sequence of past climate and landscapes compatible with the marine isotope stratigraphy.

Three supplementary procedures (unconformity-bounded, genetic sequence and event stratigraphy) applicable for the reconstruction of large-scale stratigraphical frameworks are dealt with in more detail in *section 2.6*. The potential of these units and syn- and post-sedimentary features in relation to global chrono- and (climate type) event correlation is also considered. They largely determine the success of a spatio-temporal framework reflecting the palaeoclimatic and palaeoenvironmental events on the European continent.

Chapter 3 gives an outline of the contemporary Middle Pleistocene stratigraphy of Northwest and Central Europe. *Section 3.1* discusses the limitations and (time-)stratigraphical problems with regard to the classical European palaeoclimatic models for the Pleistocene terrestrial succession. The material building elements, from which the local and regional stratigraphies are constructed, are dealt with in *section 3.2.* Five broad categories of major depositional settings and their sedimentary products are reviewed, together with some significant local-scale depositional environments and (syn- and post-) depositional features. Moreover, climatic interpretation and large-scale stratigraphical significance of these sequences, from which the Cromerian, Elsterian, Holsteinian and Saalian palaeoclimatic stages are inferred, is discussed. The bio- and chronostratigraphical control on the land-based sequences are considered in the *sections 3.3 and 3.4*, respectively.

In *Chapter 4* the local and regional stratigraphies are informally assigned to a continent-wide framework using multidisciplinary types of correlation and including principles of sequence and event stratigraphy. The approach adopted is to group genetically related sedimentary units, bounded by unconformities of regional extent and significance in the different geotectonic type regions (*section 4.1*). The units are then arranged according to superposition, litho- and biofacies characteristics, interpreted depositional environment and independent dating into a large-scale framework (*section 4.2)*. A compilation of the most up to date versions of the Northwest and Central European local stratigraphies is given in *section 4.3*. Subsequently, in *section 4.4*, relevant genetic sequences are associated with major climate-driven geological events (such as glaciations and marine transgressions) and regional tectonic events; an approach analogous to event stratigraphy. Provisional names for synthems and genetic sequence groups are introduced. They are compiled in a stratigraphical framework in which local-scale palaeoclimatic features are embedded. The main difference from the conventional (climato)stratigraphical systems concerns the hierarchical approach with regard to scale and order/magnitude of the depositional sequences.

The spatial component of climatic and environmental change must come from local key stratigraphical sequences in the fragmentary continental record. Since classification starts in the field, one of the essential steps in data inventories is to return to more or less basic geological procedures and begin with the local identification and description of objective sedimentary units in the (literature on) the sections and cores. Then, data may be structured on the basis of criteria of regional significance (e.g. bounding unconformities) and interpretation and correlation of local depositional sequences can be carried out. Testing of this approach has been done by short fieldwork studies, discussed in *Chapter 5*, in the Neuwied Basin of the Middle Rhine type region (the Kärlich and Ariendorf sections, *section 5.2*) and in the Subhercynic Basin (the Schöningen sections, *section 5.3*), both located in the German uplands. These important sites contain regional information on Middle Pleistocene conditions with potential for interregional correlations (*section 5.4*).
In seeking an overall framework for the Northwest and Central European terrestrial stratigraphy, relations between the different regional event-stratigraphical units and the marine isotopic stages (MIS) are reviewed in *Chapter 6*. The global significance of the continuous marine isotope record (*section 6.1*) is used as a template upon which the local and regional scale records are fitted. Comparison and matching of the land-based Middle Pleistocene framework with the marine isotope stratigraphy is considered in *section 6.2*. Both records are keys to different parts of the climate system. Recognition and timing of the boundaries and events from the MIS's on land may help to improve (chrono)stratigraphical control over the European sedimentary sequences, although they remain of low resolution and are therefore not interchangeable with formal time stages. Two isotopic stage boundary levels are used to fit the large-scale glacial, periglacial and marine depositional cycles within the Middle Pleistocene Subseries (*section 6.3*). Finally, the stratigraphical positions of local terrestrial evidence within the MIS-fixed time framework is dealt with in *section 6.4*.

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[1] *With the exception of the last 10,000 ^{14}C years, representing the Holocene Epoch, the Quaternary Period corresponds to the complete Pleistocene Epoch. Therefore their names are used broadly as synonyms in relation to past climatic and environmental change.*

[2] *That is the chronostratigraphical interval corresponding with the Quaternary deposits. Its duration is depending on the definition of the lower boundary which is formally set at 1.8 Ma (see also section 2.2.2).*

[3] *Based on work from Emiliani (1955) and Shackleton and Opdyke (1973).*

[4] *Including relevant sedimentological, faunal and floral evidence next to archaeological data from over 500 European localities*

[5] *Spanning the period from approximately 780 ka to 130 ka ago (Fig. 1.1).*

[6] *As also used in sedimentary basin analysis (section 2.6.2).*

Chapter 2

QUATERNARY TERRESTRIAL STRATIGRAPHY AND CORRELATION; A MULTIDISCIPLINARY APPROACH

2.1 Stratigraphical subdivision: some basic concepts and procedures

The stratigraphical subdivision of the Quaternary record forms a principal research field of the earth sciences. Indeed Quaternary geology has developed as a separate subdiscipline in relation to pre-Quaternary geology because of the different techniques and methodologies which were most appropriate to apply. For a better understanding this section is dedicated to some relevant issues on stratigraphical concepts, procedures, terminology and correlation, as well as problems in these regarding the nature of the Quaternary terrestrial sequence.

Stratigraphy or ‘the science of rock strata’ (Hedberg (*ed.*) 1976) is primarily concerned with the observation, description, interpretation and subsequent classification of stratified rocks and sediments[1]. Observation and description include, in addition to the original succession and age relations of the investigated strata, their lithological composition, fossil content, form, distribution, geophysical and geochemical properties. Interpretation, the ultimate goal of stratigraphy, concerns the mode and origin of depositional environments and the geological history. Classification of the characteristics and features of the geological successions is carried out at different scales, both spatial and temporal, and by means of various methods and techniques.

Procedures to follow have been formulated in several (inter)national stratigraphical codes and guides. Recommended rules for classification, terminology and procedures are outlined in the International Stratigraphic Guide (ISG) (Hedberg (*ed.*) 1976 and Salvador (*ed.*) 1994). They advocate a widely accepted set of tools and terms to improve world-wide communication, co-ordination and understanding among stratigraphers.

Stratigraphy starts in the field. Local-scale geological data from sections and cores and from different depositional environments are the basis for subdivision. Each classification system, by definition, is arbitrary and has its own hierarchy in which the upper category always includes the foregoing levels[2]. Basic stratigraphical procedures are lithostratigraphy, biostratigraphy and chronostratigraphy (*Figs. 2.1a* and *2.1c*). They serve best for marine and non-glacial sequences deposited in large-scale sedimentary basins spanning (tens of) millions of years, but are not quite satisfactory for the geologically short time span of the Quaternary with its highly varied terrestrial depositional record, the predominance of erosional surfaces and the absence of distinctive fossils. Available geomagnetic and geochronometric[3] dating methods are so far also inaccurate for the high resolution desired for the subdivision of this period.

Nonetheless, there are many kinds of Quaternary stratigraphical data that are useful in certain areas or for certain purposes. Data derived from a range of complementary techniques such as palaeomagnetic dating, geochronometric dating, geochemical analysis and seismic research can be of stratigraphical value and are frequently applied in smaller-scale subdivisions. Oxygen isotope stratigraphy applicable to ocean floor and ice cores has proved its effectiveness for global correlation of glaciation and deglaciation events and its potential to serve as a global time-based reference framework (*section 2.5.3* and *Chapter 6*).

2.1.1 Material descriptive units

The material basis of a geological subdivision is of a lithostratigraphical type. Lithostratigraphical units, such as formations, should be based on a unit stratotype. The stratotype defines and identifies the type and rank of the stratotype[4] (including its boundaries), the history of the concept, locality and region details, the lithological characteristics, the name, information on the genesis, the geological age and correlation with other units (Hedberg (*ed.*) 1976, Schoch 1989). Marker beds of regional importance may be common occurrences, such as till beds and loess sheets or occasional occurrences like volcanic ash horizons. Due to regional variations the lithostratigraphical units and the boundaries of most European classification systems are based on different stratigraphical criteria, such as petrographical and mineralogical composition, calcareous content, fossil content, morphological position and observed pedogenetic processes. The latter two criteria have otherwise developed into individual stratigraphical concepts additional to the lithostratigraphical subdivision of strata.

Biostratigraphical units are based on the evolution and (dis)appearance of faunal and floral taxa (the biotic components) in the deposits, dividing the fossil succession fundamentally into biozones (Hedberg (*ed.*) 1976). Both palaeozoology and palaeobotany contribute to biostratigraphy. The type of biozone that is commonly used in Quaternary stratigraphy is the assemblage-zone, comprising strata with a distinctive fossil assemblage (faunal zones respectively pollen zones). Biostratigraphical evidence, in particular palaeobotanical data, result in more detail for identification and limitation of local sequences within the non-glacial deposits of Northwest and Central Europe. Because time-transgressive overlap is conceivable as a consequence of geographical variations and because of homotaxial[5] miscorrelations, both litho- and biostratigraphical systems should be kept apart.

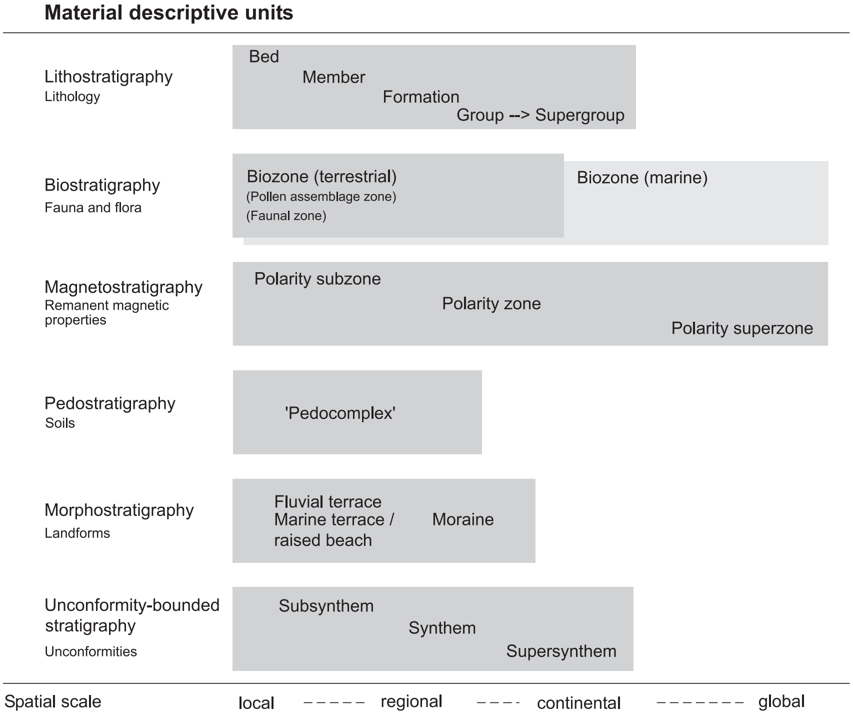
In the latest edition of the International Stratigraphic Guide (Salvador (*ed.*) 1994) two additional procedures are formally recognised which have become increasingly functional in terrestrial stratigraphy (*Fig. 2.1a*):

- magnetostratigraphy, based on changes in the remanent magnetic properties acquired during deposition of rock bodies which among others involves the polarity of the earth’s magnetic field. Basic units are the polarity zones,
- unconformity-bounded stratigraphy, based on regional significant discontinuities in the succession such as erosional breaks and surfaces of subaerial exposure (i.e. palaeosols), dividing the sequence into synthems. Unconformity-bounded units include multidisciplinary descriptive information allowing for more reliable interpretation and (chrono-) correlation over large areas. They play an important role in the establishment of a continent-wide stratigraphical framework and are further dealt with in *section 2.6.1*.

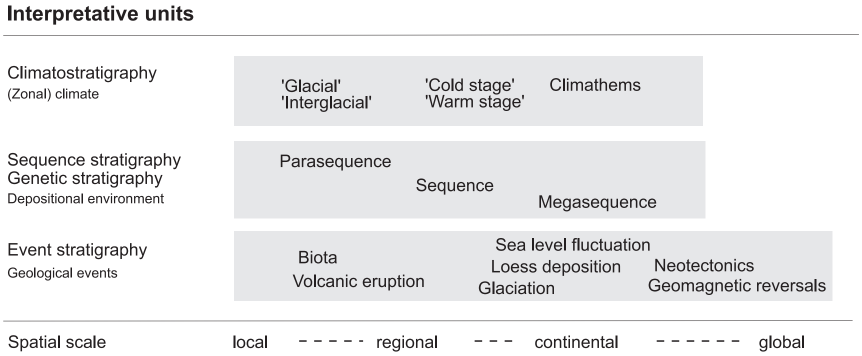
2.1.2 Interpretative units

Interpretation is, apart from observation and description, another primary concern of stratigraphy. Whereas the formal classification

Figure 2.1 Terrestrial stratigraphical classification and procedures:



a) classification of descriptive units as based on different sedimentary characteristics;



b) classification of interpretative units interpreted from material descriptive evidence;

systems offer ways of dividing strata into subsidiary units which are descriptive, they do not entail interpretation of genetic aspects and causal meanings concerning environmental and climatic change in time and space. Most land-based lithostratigraphical units, for example, tend to be local to regional in extent and are often not that appropriate to document the sedimentary units in terms of depositional cycles and (lateral) facies changes as depositional sequence units can do in sedimentary basins. Interpretative units (*Fig. 2.1b*) have better potential for use as a basis for large-scale correlation. Therefore, in many European countries inferred lithogenetic and palaeoclimatic criteria have been introduced in several local and regional stratigraphies to distinguish between formations deposited in different environments, e.g. in the Netherlands[6] (Zagwijn 1975). In northern Germany, formations are generally not defined and named in a formal way, but denoted by a code system in which optionally lithology, depositional environment and/or climatostratigraphical stage can be indicated (Lüttig 1958, Woldstedt & Duphorn 1974).

Climatic stages traditionally are defined from litho- and biostratigraphical evidence from stratotype localities and indicate local and regional climatic conditions at the time of deposition. Terminology is not unambiguous and the units do not have a formal status. Nevertheless, climate-based classification remains the basis for subdivision of the Quaternary succession, but should be used subsidiarily to the formal classifications and not be combined with lithostratigraphical terminology.

Event stratigraphical units, in the first instance, indicate distinct geological processes such as volcanic eruptions indicated by tephra strata. They become an interesting stratigraphical tool in Quaternary subdivision when, as in recent years, also extreme longer term climate-related events become included. Glaciations and marine transgressions, interpreted from sedimentary sequences, are large-scale events that can be correlated over long distances and that can be used across the terrestrial-marine boundary.

The recognition of depositional environments, climatic signatures and/or events from the fragmentary and highly variable terrestrial succession are by their nature inferential methods and by no means straightforward. Sequence and event stratigraphy are discussed further in *section 2.6*. Climatostratigraphy is dealt with more comprehensively in *3*.

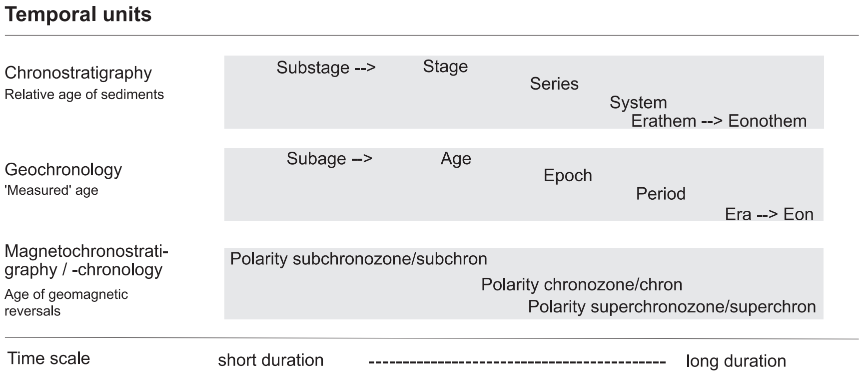
2.1.3 Temporal units

Chronostratigraphical units (*Fig. 2.1c*) divide the sedimentary column, when possible, according to the geological age and time of formation of the strata into subsidiary stages (Hedberg (*ed.*) 1976). At a higher-level rank these are grouped into series and systems. Chronostratigraphical units are by definition isochronous and topless, that is only their lower boundary has to be defined at a boundary stratotype, preferably within a sequence of continuous deposits. Chronostratigraphical units and boundaries are generally interpreted from calibrated points ('spikes') in type sections ideally in sediments of marine origin. These are used for large-scale (interregional) correlation along supposed synchronous surfaces[7]. The most significant problem in Quaternary terrestrial chronostratigraphy is the lack of such isochronous boundary-stratotypes and hence of formal stages, restricting the application of 'pure' chronostratigraphy in the formal conventional sense. In order to correlate the local sequences to a regional or global timescale, climate-based stages have often been used as direct equivalents of chronostratigraphical stages. They are, however, not since they are interpreted from incomplete and diverse sequences with diachronous time boundaries. This has given rise to much nomenclatural confusion and correlation problems. Nevertheless they indicate the relative age and regional scale of sequences.

Chronostratigraphical units correspond to temporal non-material units called geochronological units, respectively ages, epochs and periods. Mainly as a result of the progressive development of geochronological techniques and methods during the last five decades, Quaternary chronology is no longer confined to the relative information derived from conventional stratigraphical methods. Isotopic and radiometric dating methods yield reliable ages up to some 100 ka for suitable sediments and fossils. Important time markers of global significance concern the geomagnetic reversals of which the Matuyama/Brunhes reversal at about 780 ka has been proposed the boundary of the Early and Middle Pleistocene subseries (Butzer and Izaac 1975, Richmond 1996). Dating and tuning of ocean and ice-core sequences through astronomical cycles has been proven a valuable geochronological tool revealing high resolution reference scales for the timing of large-scale palaeoclimatic events.

2.1.4 Correlation

Finally, correlation is an essential procedure to show correspondence in character and (relative) stratigraphical position between stratigraphical units and features that are geographically separated (Hedberg (ed.) 1976). Although the term correlation is used in a broad sense to refer to all kinds of spatial correspondence and/or equivalency based on objective characteristics, correlation eventually serves to determine time relationships between strata and features. Within the scope of a global time standard, chrono-correlation comprises the interpretation of all types of data indicative for temporal relationships between stratigraphical units (*cf.* Holland 1998). There are, however, very few means of directly correlating between the terrestrial sequences and those in the oceans. In the absence of useful markers or index fossils in both the diachronous units of terrestrial environments and marine continuous successions, chrono-correlations will never be perfect, but their precision can be increased by using event-stratigraphical features.



c) classification of temporal material units based on the geological age and time of formation.

2.2 The Quaternary System and Period

2.2.1 Terminology and historical background

The development of a stratigraphical nomenclature for solid rocks, sediments and time to determine a sequence of events in the earth's history (and life on earth) started around 1760 with rough classifications of mountains and rocks in Tuscany, Italy by Arduino and in Germany by Lehmann. Arduino used a fourfold classification and was the first who introduced the term Quaternary with which he classified the loose alluvial sediments eroded from the Tuscany mountains.

Between the late eighteenth and first half of the nineteenth century three principal divisions had been established in Western Europe, based on fossiliferous strata (discussed in Lyell 1853):

- Primary, later termed Palaeozoic meaning 'ancient life'
- Secondary, later termed Mesozoic ('middle life')
- Tertiary, later defined as the first part of the Cenozoic ('recent life').

Although these three divisions were bounded by major unconformities believed of chronostratigraphical significance, the major criterion for subdivision and correlation was palaeontological evidence rather than the numerical time of formation.

The term Quaternary was re-introduced in 1829 by Desnoyers, to refer to the deposits unconformably overlying the Tertiary sequence in the Paris Basin and containing fossils of species, which are still living today (Reboul 1833). On the basis of fossil molluscs, Lyell (1839) introduced the term *Pleistocene* (meaning 'the most recent') to refer to deposits of the last time period (Epoch) of the Tertiary System, which he had earlier referred to as *Newer Pliocene.* He termed Post-Tertiary deposits *Recent* referring to all rocks that had formed since the appearance of man.

The (late) eighteenth and nineteenth century researchers from different parts of Europe already indicated the complex and heterogeneous nature of the uppermost, non-consolidated deposits compared to other rock successions. Because its contained fossils, if present, appeared to have pronounced modern affinities the association with the youngest geological time period was a plain fact. Nevertheless, palaeontological-distinguishing criteria for their classification and correlation at a system level appeared to be insufficient[8].

Apart from (palaeontological) classification, a variety of conceptions were put forward on the genesis of the different superficial deposits, in particular with regard to the provenance of erratics, which had been found in many terrestrial deposits and at the land surface. Explanations were sought in respectively the biblical flood theory (Von Buch 1815, Buckland 1823), the drift theory (Lyell 1833) and the glacial theory. Former glaciations in the Alps and elsewhere had already been inferred from the close of the eighteenth century, which was first published by Hutton (1795) followed by Playfair (1802) and Venetz (1821) among others. In southern Germany, the term *Eiszeit* (Ice Age) had been introduced in 1837 by Schimper to bear on the geological period of glaciations. The corresponding deposits were assigned to the *Diluvium*, the postglacial deposits to the *Alluvium*. Both terms were originally introduced in relation to the biblical flood theory, but persisted in Germany up to the middle of the twentieth century. Von Morlot in 1855 re-introduced the term Quartär to refer to the ice age era. General acceptance of the glacial theory was gradually gained after lectures given by influential scientists like Agassiz (1840 in Britain, 1846 in North America) and Torell (1875 in northern Germany). It was Forbes (1846) who used Lyell's Pleistocene to refer to the '*Glacial Epoch*' and implied a post-Tertiary age which was only accepted by Lyell 'the father of stratigraphy' in 1873. The base of the Pleistocene was equated with the first glacial deposits associated with the classical mid-latitude glaciations in Europe. The term *Recent* from then on became restricted to the post-glacial period, and was renamed the *Holocene* (meaning 'wholly recent') at the 1885 International Geological Congress (IGC) in Birmingham.

Lyell's initially biostratigraphical concepts and their subsequent evolution into climate-related post-Tertiary Pleistocene and Recent stratigraphical units comprised all that is termed Quaternary today. Nevertheless, the term Quaternary was for long only generally adopted in the Mediterranean region where, due to the lack of glacial deposits, the first occurrence of cold fauna and flora in marine and continental deposits was used to delimit the post-Tertiary period (Pareto 1865, Seguenza 1868, later Haug 1910-1913: in Vai 1997).

It was not until 1948, at the IGC in London, that these two regional stratigraphies of the uppermost (cold climate-dominated) sequence were formally combined (King and Oakley 1949). In order to devise a worldwide standard time scale, the IGC then recommended the Quaternary as the last *System* of the global chronostratigraphical scale and the last *Period* of the geochronological scale. Together with the adjacent Tertiary *System*/*Period* it constitutes the Cenozoic *Erathem*/*Era*.

2.2.2 Age and chronostratigraphical status

The IGC in 1948 also recommended that the beginning of the Quaternary and hence the Plio-/Pleistocene boundary should be defined at the first indication of a distinct climatic deterioration in what was assumed to be a complete Neogene succession from the type area in southern Italy. Based on mollusc and foraminiferal fauna this event was recorded at the base of the marine Calabrian Formation (*cf.* Gignoux 1913).

The age of the Plio/Pleistocene boundary at the Vrica section in southern Italy, adopted at the IGC in Moscow 1985 as the GSSP[12] (Aguirre and Pasini 1985), is now estimated near the top of the Olduvai normal Subchron at 1.8 Ma (*Fig. 1.1*). Firm evidence from both marine and terrestrial sequences in the northern hemisphere however indicates that the earliest cold climate conditions roughly coincide with the Gauss/Matuyama palaeomagnetic reversal at 2.6 Ma (in Suc *et al.* 1997), at the base of the Galesian Stage (*Fig. 1.1*). These concern:

- The first appearance of cold floras in the Praetiglian cold stage of the Dutch stratigraphy, which occurred immediately after the Gauss/Matuyama transition (Zagwijn 1974),
- The faunal change in Europe from forest dwellers to grassland/steppe elements (the '*Elephas-Bos-Equus*' event) coinciding with the Gauss/Matuyama transition (Bonifay 1990),
- The beginning of the loess deposition in China, Central Asia and probably also in Central Europe dating from around 2.5 Ma (Kukla and An 1989, Dodonov 1991, Ding *et al.* 1992, Tyracek 1997),
- The appearance of various biological markers pointing to the cooling of surface waters in the Mediterranean Sea (Combourieu-Nebout and Vergnaud-Grazzini 1991), and
- The first occurrence of abundant ice-rafted detritus (IRD) in the mid-latitude North Atlantic deep-sea sediments (Shackleton *et al.* 1984, Mangerud *et al.* 1996) with an age of about 2.6 Ma. The latter incursion corresponds to the cold Marine Isotope

Stage (MIS) 104 in the oceanic record (Shackleton 1997) which is followed by the well-defined cold events MIS 100, 98 and 96.

Thus, today many stratigraphers generally acknowledge, although do not agree, that the global Tertiary/Quaternary climatic turnover may date back as far as 2.6 Ma. This is significantly earlier than the classical Pleistocene glacial stages of northern Europe, all which are younger than 1 Ma. A lowering of the Plio/Pleistocene boundary coinciding with the Gauss/Matuyama palaeomagnetic reversal and with glacial MIS 104 brings about excellent and practical correlation potential in both marine and terrestrial sequences (Partridge 1997). The terrestrial Quaternary deposits then correspond to the approximately 2.6 Ma interval of the marine-based astronomical polarity time scale which is regarded the best reference framework delimiting and correlating the semi-synchronous stages and events within the Quaternary.

In conclusion, the status and conception of the Quaternary in the standard geological timescale remains a stratigraphical dilemma and an ongoing subject for debate. The geologically short time span of the Quaternary Period, together with the incompleteness of its system, particularly the terrestrial part, makes palaeontology of limited use as a primary criterion for chronostratigraphical subdivision. The high precision that is desired for the subdivision of the Quaternary simply cannot be achieved by traditional palaeontological zonation. Moreover, palaeomagnetism is of low resolution and (reliable) geochronometric dating methods, which reach beyond the radiocarbon dating limit of 40-50 k, are lacking.
On the other hand, when compared to earlier systems the deviant nature of the Quaternary record, dominated by cyclic zonal climatic change (well represented in the oceanic record), together with its different temporal scale and resolution are arguments to support the Quaternary as a discrete system rank unit. Despite some efforts which have been undertaken (Aubry *et al.* 1999) only the base of the Quaternary at Vrica is formally defined a GSSP until now. The International Subcommission on Quaternary Stratigraphy (ISQS) is in the process of defining GSSPs in the Quaternary system for the Early/Middle, Middle/Late Pleistocene and the base of the Holocene. For practical reasons the boundary levels of the marine isotope stratigraphy are commonly used as a reference and matched with regional stratotypes on the continents. This conception still meets criticism on the basis of traditional stratigraphical principles and methods (a.o. in Schoch 1989 and Gradstein *et al.* 2002). In every respect the status of the Pleistocene will remain Series/Epoch incorporated either within the Tertiary/Neogene System/Period or the Quaternary System/Period.

2.3 Nature of the Quaternary terrestrial succession

2.3.1 The incomplete terrestrial geological record

As already mentioned in the introduction, the main problem of continental Pleistocene stratigraphy concerns its highly fragmentary and genetically-varying depositional and fossil succession. Hiatuses form a substantial part of the terrestrial record since the Pleistocene sequences are dominated by erosional unconformities. Sequences in which continuous deposition over long time-spans can be observed are very rare and regionally scattered. Therefore even relative dating poses problems. Moreover, there is a paucity of usable (index) fossils and a lack of widely applicable dating possibilities in general[9]. These characteristics determine, not to say dictate, the classification levels and the paradigms, which have been historically developed. Objective distinguishing criteria for natural, correlative units are restricted and hence the spatial and temporal scale of their interpretation concerning past climate and environment. And, given the fragmentary record, Penck and Brückner (1901-1909) and other early twentieth century researchers (*section 3.1.1*) obviously had to conclude that there were maximally four glacial stages accompanied by major glacier or ice-sheet expansions in the Alps and northern Europe. The virtually continuous Quaternary records from ice- and deep-sea cores, the use of multidisciplinary data, brought in both by advanced techniques, and larger scale interests has put the classical methods and paradigms concerning the terrestrial European record more and more in perspective. The widening of the focus from regional to global-scale processes has also enlarged the scale of interpretation. Plate tectonics, atmosphere-glacier-ocean interactions and eustatic sea-level changes, for example, require for their recognition and magnitude an interpretation of observed stratigraphical relationships preferably supported by independent dating. Nevertheless, local geological evidence remains the basis for classification and palaeoclimatic interpretations. Hence it follows that their resolution, both spatial and temporal, remains restricted by the nature of the sequences.

2.3.2 The interpreted terrestrial palaeoclimatic record

Yet, the mid-latitude European stratigraphical record comprises the history of repeated large-scale ice-sheet expansions and periglacial phenomena, interrupted by marine sea-level maxima, and organic lake and mire deposition and/or soil formation. These reflections of climate forcing remain the basis for stratigraphical classification of the Pleistocene Series, both in the terrestrially based and ocean-core stratigraphies.

A meaningful worldwide climatostratigraphical subdivision of the Pleistocene can only be based on continuous depositional sequences provided with an accurate and high-resolution chronology, such as has been established in the last three decades, entirely based on open marine sequences. Unlike the marine sequences, cyclic variations in continental successions cannot yet be accurately dated. Nonetheless, this fragmentary and widely-spaced record is important. Long, continuous terrestrial records, of which the interpreted palaeoclimatic information can be matched with the trends in the oceanic record, are so few that the spatial component of change, many indices of palaeoenvironment and also records of human activity, would be very poorly represented without them. These local-scale reference records are invaluable templates onto which the fragmentary record may be fitted. Stratigraphy therefore has to operate at both global and local levels, to include the continental record in the astronomically tuned marine record and to integrate different independent evidence.

Thus, questions such as 'What do local interpretations of climate tell us about regional or global climate?', or the opposite, 'What are the local effects of global climate change?' are only and best answered by extrapolation of long (semi-) continuous sequences to the global oceanic record. The few long records in Europe, which extend over at least one Pleistocene glacial cycle and which play an essential chrono- and climatostratigraphical role as references, include:

- The lake sequences from Tenaghi Phillippon (Greece), containing pollen records spanning about the last 1 Ma (Van der Hammen *et al.* 1971; Mommersteeg *et al.* 1995),
- The over 300 ka long pollen record from Lac du Bouchet and

Praclaux in France (*Fig. 3.9*, de Beaulieu & Reille 1995, Tzedakis *et al*. 1997, de Beaulieu *et al*. 2001), and

- The Late Pleistocene pollen records from La Grande Pile and Les Echets in France (Woillard 1979; de Beaulieu & Reille 1987; Guiot *et al*. 1989, 1992).

Further important key stratigraphical sequences within Europe, although not continuous or superimposed, include:

- The combined loess/palaeosol and river terrace sections of Červený Kopec (in Slovakia, *Fig. 2.2*) and Krems (in Austria), spanning 9 glacial cycles within the Brunhes Chron (Kukla 1970, Fink & Kukla 1977),
- The Middle Pleistocene loess/palaeosol terrace sections with intercalated volcanic ash horizons of Kärlich and Ariendorf in the Middle Rhine valley in Germany, (a.o. Brunnacker *et al.* 1969, Schirmer (*ed.*) 1990, Boenigk 1995, Turner (*ed.*) 1997, Boenigk and Frechen 2001: *section 5.2*),
- The Somme valley terrace sequence in France (Antoine 1990 and 1994, Antione *et al.* 2003),
- The terrace sequence of the lower Thames valley (Gibbard 1985, Bridgland 1994, Schreve and Bridgland 2002),
- The Bilzingsleben terrace sequence in Thuringia/Germany (Mania 1993),
- The Schöningen sections in Lower Saxony/Germany (Thieme *et al.* 1993, Urban 1995) intermediate between the Elsterian and Saalian glacial sequences (*section 5.4*).

Unfortunately, most of these local records from Europe, each of limited duration, are scattered over the extraglacial areas, located in different geotectonic type areas and are, also as a consequence of interfering regional tectonics, not easily correlative with the wide-spread sediments of the ice-sheet expansions in northern Europe. Nor are they easily related to the marine transgressional sequences in the North Sea basin. Yet, an overall picture of the past terrestrial climate record has to be compiled from these well-known, localised key sequences. The reliability of the synthesis depends on the accuracy of the correlations between the various sequences and events (*cf.* Cooke 1984) which can be increased by indirect correlation and trend-matching with Eurasian reference loess records and the deep-sea records (*section 6.2*).

2.4 Scale and resolution of research

Scales play an imported role in the recognition and analysis of geological evidence. The concept of scale is considered as a measure, both spatially and temporally, involving the size (small to large sized) and duration (short to long duration) of stratigraphical units (*Fig. 2.1*). In fact scale is considered twice during research (Stein and Linse (*eds*.) 1993): once when describing evidence, the scale at which objects are observed and measured, and again during interpretation, spatial and temporal scales at which reconstructions are made and processes are explained.

In addition to scale, the concept of resolution at which an object or a period of time is considered is of importance. In mapping, large and small scale refer to respectively high and low resolution images of areas. When related to temporal scales, resolution refers to the length of the temporal intervals that are considered, e.g. events reconstructed for short-term time periods are at high resolutions.

Accordingly, scale involves the size and resolution of the described observations (minerals, beds, outcrops, formations), as well as the spatial and temporal resolution of the interpretation. Furthermore, the scale of interpretation incorporates resolutions dictated by the nature of the record (see previous section). Thus, the global implications of the fragmentary and largely undated continental Quaternary record therefore must be constrained to large-scale interpretations and low-resolution classification, at least beyond the radiocarbon dating limit of 40-50 ka. For the Middle Pleistocene this implies that in the best case the trends in the 100 ka climatic cyclicity of the marine isotope stratigraphy can be correlated. Only in some cases it will be possible to match short-term oscillations.

2.4.1 Spatial scale

Sediments and fossils are measured in three dimensions, microscopically as well as macroscopically. Their properties are described, interpreted, subdivided and mapped for different applications. Scales at which one operates in earth scientific stratigraphy, from large scale (= high resolution) to small scale (= low resolution), are:

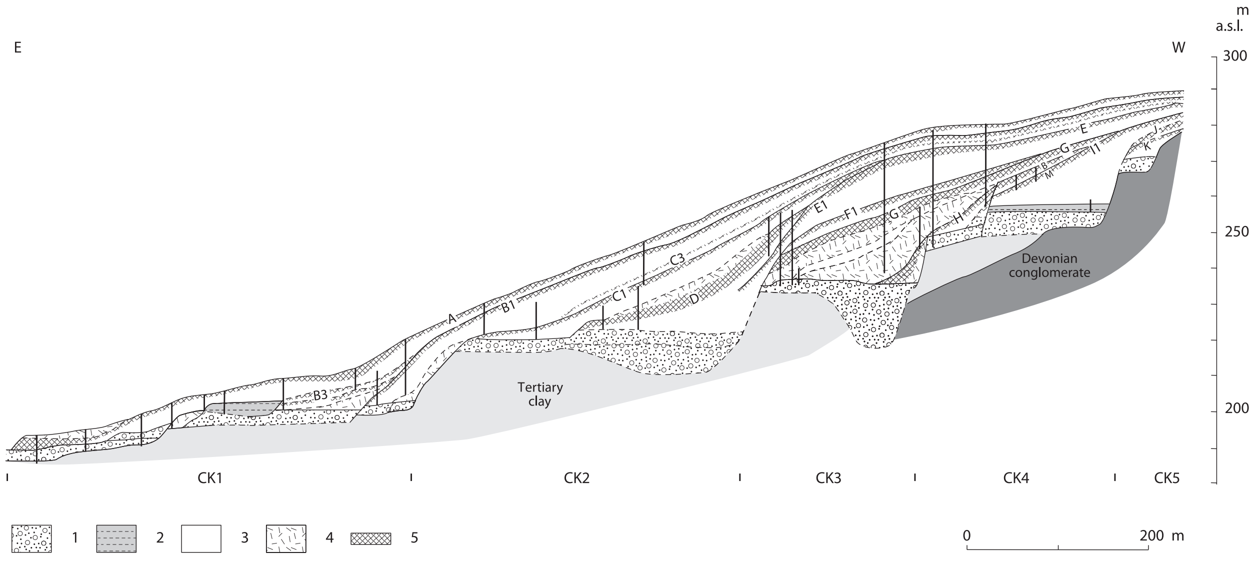


Figure 2.2 The terrace profile from Cervený Kopec along the Srvatka river and interpreted loess/palaeosol cycles (Kukla 1969, 1975). 1) fluvial terrace gravel; 2) fluvial silt; 3) loess; 4) slope deposits; 5) soil complex. For subdivision and environmental interpretation see Figure 3.2.

- *Local-scale stratigraphies* comprising subdivisions and interpretations deduced from observations made at the scale of sites and small areas, the latter of which are both naturally and arbitrarily (i.e. politically) bounded. They may be established for: a) boreholes; b) artificial open air sections; c) sequences in lakes, stream and river valleys, small-scale tectonic or sedimentary basins, and d) geographically small areas, such as counties or provinces. Litho- and biofacies characteristics and interpreted depositional (sub-)environments generally are described and examined in great detail at a local scale. Distinguishing criteria often are of local significance. The mapping scale, ranging from 1:10,000 up to 1:250,000, allows representation of low levels of classification.
- *Regional-scale stratigraphies* are established for larger areas which are considered coherent spatial units, again both limited by natural and arbitrary boundaries. Although based on local evidence, generalisations must be made to distinguish homogeneous units that can also be mapped. Mapping scales may vary from 1:100,000 to 1:1,000,000. Criteria usually are of a higher rank than for local stratigraphies because local stratal units are often impersistent and lithological properties fails to suffice since lateral variations are too large. Lithogenetic aspects and lithofacies assemblages are then considered to obtain unity.
- *Continental-scale and global-scale stratigraphies* require interpreted sedimentological and biological evidence for the reconstruction of continental and global events, mostly occurring over long periods of time, that overrule regional and local effects. The marine isotope stratigraphy shows that climate is the only variable in the Pleistocene of global significance that controls the abiotic and biotic components and processes of the earth's surface. Thus, geo- and bio-information on global climatic change must be selected, although they have to be corrected for local and regional impacts such as (neo) tectonic activity, latitude and altitude. In practice this selection implies that determination of the potential for correlation precedes classification; a theme further discussed in *section 2.5.1*.

2.4.2 Temporal scale

Temporal scales are commonly only considered in the interpretative phase of (earth scientific) research. The preferred scale at which the interpretations are made range from the Holocene Substages (at thousand year scale) to the entire Cenozoic Era (millions of year scale), depending on the nature of the record, the research objectives and the applicability of dating methods. On the geological timescale, the events of interest, such as tectonic cycles of subsidence and uplift or eustatic cycles of rising and falling sea-level, occurred over very long time periods, over wide areas and involve many earth systems. Measured in time-intervals at the millions of year scale an hierarchy of controlling cyclic (geological) events can be distinguished (*cf.* Miall 1984, 1990):

- *1st order cycles* (>50 million years), such as those related to continental drift and plate tectonics,
- *2nd order cycles* (3 - 50 million years), for example, those involving basin evolution stages,
- *3rd order cycles* (0.5 - 3 million years) in which global eustatic sea-level fluctuations occur resulting from palaeogeographical differences by epeirogenesis. They may interfere with 4th order glacio-eustatic sea-level fluctuations,
- *4th order cycles* (0.1 - 0.5 million years) involving autocyclic processes such as insolation rates as a control on latitudinal climate zonation and hence the distribution of glaciers, periglacial areas and ocean currents,
- *5th and higher order cycles* concern short-term cyclic events operating on time scales smaller than 0.1 million years. They vary from oscillations of ice-sheet margins, volcanic eruption phases to floods and storms.

Resolution usually decreases with the age of the deposits. Dating methods have contributed to the temporal resolution of interpretations, in particular for the Holocene and part of the Late Pleistocene. Dendrochronology is very precise, but is only applicable to Holocene records. The resolution of radiocarbon dating is somewhat lower, covering about the last 40-50,000 years. For the remaining part of the Pleistocene one has to rely largely on stratigraphical position[10], changes in biota, palaeomagnetic data and occasional geochronometric dating from suitable sediments and fossils.

2.5 Aims of subdivision: a global framework for regional stratigraphies

The research objectives for subdivision in this thesis, as already explained in *section 1.1*, comprise considerations concerning an alternative approach supplementary to the traditional climatostratigraphical procedure. Three items will be dealt with in the next sections that can be regarded as subsequent steps in comparing terrestrial to marine stratigraphies:

- Arrangement of an informal, genetically-based framework from local stratigraphical evidence within the natural type regions in Northwest and Central Europe, using unconformity-bounded and genetic sequence stratigraphical principles,
- The interpretation and recognition of palaeoclimatic and tectonic events and cycles within this frame and interpretation of their scale order,
- Searching for boundary levels and time-ranges for the climate type events in the marine isotope stratigraphy to provide a supplementary basis for the chronostratigraphical position of the terrestrial sequences. This implies the supposition of an intermediate link between the (semi-)synchronous global-scale events in order to give clues to the palaeoclimatic terrestrial sequence.

2.5.1 A supplementary large-scale stratigraphical framework for regional stratigraphies

Most present-day stratigraphies are build on a combination of litho- and biostratigraphical units, to which morpho-, soil- and magnetostratigraphical elements are frequently added. To bring together these units of primarily local interest and a chronological sequence of (climate-induced) events valid for the European continent, by superposition, correlation and dating, has been proven very problematic (*section 3.1*).

In continental sedimentary environments, where lateral facies variation and erosion are important, the (formally classified) litho- and biostratigraphical elements represent lenses isolated from each other in time and space. These elements are deposited in a variety of environments, located within the different geotectonic settings of Europe, as well as situated in different geographical and morphological positions. They may be widely distributed or restricted to one locality.

In the complex task of ordering the terrestrial succession in time and space, the utility of different sedimentary, erosional and pedological elements in constructing a regional stratigraphical sequence, based on superposition, (spatial) correlation and independent dating, depends upon:

- Sedimentary units deposited by wide-spread events and their bounding unconformities,
- Infrequent events which leave highly distinctive evidence in the sedimentary record,
- Environments in which continuous or near continuous sedimentation takes place over long time periods (which are generally at local scale in the terrestrial realm),
- Sediments or fossils appropriate for dating.

Using the above-mentioned criteria is very helpful in explaining the fragmentary and repetitive nature of the Quaternary terrestrial record in terms of how depositional environments and ecosystems respond to climatic and (neo-) tectonic cyclicity, both at local scale and in establishing a continental sequence of climatically-induced geological events. On a regional and global scale workers need to consider the underlying controls that govern the formation of sequences in different depositional environments and their vertical and lateral distribution. As mentioned previously, the main cyclic variables are universal climate and regional tectonics, next to geomagnetic polarity. Since both work at different temporal and spatial scales, an analysis of their impact on the preserved regional depositional sequences is of great importance. This implies that correlation potential may precede definition of interpretive units. This is an approach comparable to the concepts of genetic sequence stratigraphy and event stratigraphy dealt with in *section 2.6*. Both concepts have become increasingly important as components of stratigraphical correlation.

The supplementary genetic sequence- and event-stratigraphical frameworks, combining relevant regional geo-, bio- and chronological information on sedimentary environment, climate change and tectonic activity, provide better clues to large-scale interpretation and correlation than building (inter)regional sequences of merely interpreted climatic stages, as will further be explained in *section 3.2*. The Holsteinian warm Stage, for example, refers to different climatic interpretations from different sedimentary environments, such as marine transgressive sediments at the North Sea basin margins, forest assemblages from lacustrine sequences and to weathering and soil processes. By classifying the genetic character of these features with reference to the depositional environment of the units, to their stratigraphical position in the type locality or type region and, when effective, to the interpreted climate-driven environmental event from which they originate, the problem of differently defined time-transgressive unit boundaries has become implied and can be handled as one sees fit.

A large-scale framework in which the existing local and regional multidisciplinary data and stratigraphical relationships may be fitted and integrated requires a uniform and objective subdivision of relevant regional and continent-wide stratigraphical units and features. Synthems, including the local- and regional-scale formations (whether or not lithogenetically defined) and biozones, may form the material basis for these. They incorporate descriptive litho- and biofacies units and are associated with interpreted depositional sequences. They constitute uniformly defined units that are conform to the ISG (Salvador (ed.) 1994) and are suitable for interpretation and correlation on regional and continental scales. The proposed procedure is in many ways similar to climatostratigraphy but instead an hierarchical subdivision of inferential units is used referring to scale, depositional environment and nature of the palaeoclimatic event.

2.5.2 Interpretation of climate type events

Climatic environment varies both temporally and spatially. In both domains, transitions may be either sharp or gradational. Thus, climate driven changes in biota and sedimentology at widely spaced points may be synchronous or diachronous, whilst dating is rarely of sufficient resolution to determine which.

The sedimentary sequences of the geological record of Europe may provide estimations of the probable range, succession and duration of the climate conditions in the Pleistocene. The genetically-related terrestrial units within the unconformity-bounded framework contain the information from which the event units eligible for large-scale correlation can be identified. This information is of three types (Boulton *et al.* 1997):

1 Proxy indicators of atmospheric condition (temperature and precipitation) such as:
  - Distribution and lithofacies characteristics of glacial and glacial-related sediments and associated landforms indicating ice-sheet expansion and ice-margin positions,
  - Distribution and lithofacies characteristics of periglacial loess deposits as indicators for cold, dry conditions and solifluction deposits indicating cold, humid conditions,
  - Distribution and lithofacies characteristics of fluvial sediments in recognising climatic regime during deposition,
  - Cryogenic structures in glacial, fluvial and aeolian periglacial environments indicating the nature and extent of permafrost,
  - Vegetational composition from pollen and plant macrofossil analysis in terrestrial (lacustrine, fluvial) and shallow marine sequences,
  - Microfaunal and macrofaunal assemblages in terrestrial (lacustrine, fluvial), shelf sea and raised marine environments,
  - Soil development and weathering characteristics within aeolian, fluvial and glacial sequences,
  - Growth frequency distributions of cave calcite deposits.

2 Evidence of relative sea-level as a reflection of global and local ice volume and lithosphere flexure inferred from the distribution of paralic and shallow marine deposits such as maximum flooding surfaces, transgressive surfaces, raised beaches and incised valleys.

3 Evidence of (geo)hydrological conditions from:
  - Deposits and landforms which reflect changing river courses and groundwater levels,
  - Groundwater chemistry reflecting the nature and rate of groundwater recharge,
  - Palaeo-lake levels which reflect changes in the surface water balance.

The palaeoclimatic information included in the unconformity-bounded units of the local sequences must interact with large-scale stratigraphical frameworks. They provide a rough framework for the number and extent of large-scale (peri-)glacial and coastal marine sedimentary cycles in the Middle Pleistocene for the continental type regions in mid-latitude Europe. Their timing is reconstructed in accordance with the local terrestrial chronostratigraphical data, on the one hand, and with the global magnetostratigraphy and the marine isotope stratigraphy, on the other. Evidence for intermediate non-(peri-) glacial cycles, incorporating more detail in this hierarchical division of composed large-scale and small-scale sequences, must be interpreted from local (sub-) environments, such as lakes, abandoned fluvial channels, buried soils and carbonate springs (travertines) which are relatively widely-spaced and poorly represented. Although these small-scale sedimentary sequences provide more detailed climate proxy records by application of geochemical, isotopic, micromorphological, pedological, pollen-analytical and palaeontological investigations, their contributions to a continent-wide stratigraphy are constrained by their:

- often short and resembling records and
- numerous locally-controlled factors such as altitude, substrate, exposure and small-scale tectonic features.

This may lead to erroneous interpretations with regard to their interregional significance and timing. For example, the Late Middle Pleistocene pollen records from the lake deposits of Tenaghi Philippon and Lac du Bouchet/Praclaux are semi-continuous terrestrial equivalents of the oceanic record, showing similar overall trends of zonal climatic change. The loess/palaeosol successions in China and Eurasia of extreme cold, dry aeolian deposition and various post-depositional interruptions also correspond well to the global palaeoclimatic trends. They are the guides to the incomplete regional stratigraphies of Northwest and Central Europe, taking into account palaeogeographical and biogeographical variations as a consequence of regional climate and (neo-) tectonics.

2.5.3 Relation of regional terrestrial events to the marine isotope stratigraphy

Event-stratigraphical trend matching and time-stratigraphical correlations of the terrestrial and marine record are some of the challenges to reduce the uncertainties associated with the European Middle Pleistocene chronostratigraphy. But how is one to correlate the climatic signatures from the different terrestrial depositional environments in the type regions with that in the global marine environment?

[a] Matching of terrestrial and marine boundary levels

Progressive development of continuous records of oceanic, polar and continental climate through the late Cenozoic from deep-ocean sediment cores, ice cores and from loess and lake sediments have provided chronological frameworks for the local and regional stratigraphies on the European continent.
The present existence of the marine, global time-based reference framework as a standard forms a prerequisite in searching boundary levels for the terrestrial Pleistocene sequences and for their associated events. However, the terrestrial sequences can only be indirectly correlated with the oceanic record[11], because of the lack of chronological controls. Nevertheless, matching of curves from long loess/palaeosol and pollen records indicate that the events lie at least within the time-ranges of the marine isotope stages.

The assumption that large-scale climatic change, as can indirectly be observed in the oceanic record, is a global phenomenon may then be used as a reference to define a standard sequence of semi-synchronous event-stratigraphical terrestrial ‘stages’. In this approach, it is assumed that limits to the amplitude of regional climatic variation are set by global changes. The effects of extreme climate-driven events, such as ice-sheet glaciations, permafrost development or marine transgressions and the development of wide-spread temperate floras in the mid-latitudes of Europe, will be reflected in both global and regional records, whilst events of lesser amplitude could show spatial intensity anomalies large enough to introduce uncertainties in correlation. A mismatch between oceanic and regional terrestrial evidence of glacials and interglacials is most likely to come from absence of evidence in the terrestrial record or miscorrelations within it.
The assumption made above fits the suggestion in the International Stratigraphic Guide (Salvador (*ed.*) 1994) that the Quaternary land-based chronostratigraphical units are best defined and characterised as the intervals between designated boundary-stratotypes. But the latter are rare and of low resolution in the terrestrial record. An example are the ‘marklines’[12] in Kukla’s subdivision (1969, 1970) of loess cycles in Slovakia shown in *Figure 3.2*. They are thought to correspond to the abrupt climatic changes (deglaciations) shown in the marine isotope records at the termination of each glacial isotopic cycle. Although their time intervals comprise thousands of years, the deglaciations are the least time-transgressive change-overs in the continuous deep-ocean records. The midpoints between the most pronounced peaks of the deglaciations, are arbitrarily and informally taken as boundary stratotypes for the marine isotope stages (MIS), established from these records. The loess sequences and other terrestrial sequences reflecting rapid climatic ameliorations, represented by forest vegetation extension, sea-level rise or soil formation, have lower boundaries which may be not coeval with the midpoints of the deglaciations but they lie at least within their time-ranges. The deglaciation phases at the MIS-transitions at present appear to be the best and most useful boundary levels for extrapolation and chrono-correlation. They alternatively are considered in *chapter 6* as ‘remote boundary levels’ for the timing of the large-scale Middle Pleistocene land-based palaeoclimatic events.

On the other hand, global records are only a general guide to local climatic environment and thus a relatively poor basis for correlation. They are not very precise and merely show variations in ice volume on the continents or better, variations in the global total volume of freshwater separated from the ocean-atmosphere hydrologic cycle (Kukla & Çilek 1996), without the latitudinal zonation of climate to match. The marine (δ^{18}O-stratigraphy of the last about 700 ka is presumably largely controlled by the Laurentide ice-sheet and hence firstly reflects regional ice-volume variations in North America, which may be traceable on a global scale (Kukla & Çilek 1996, Bauch-Henning *et al.* 2000, see also chapter 6). Research on cyclically-bedded continental successions, such as ice cores from Antarctica (Vostok) and Greenland (Camp Century: Dansgaard *et al.* 1993), loess sequences from China and Tadzjikistan (Kukla *et al.* 2002, Frechen and Dodonov 1998), and several lake sequences from a.o. Colombia (Hooghiemstra *et al.* 1994), Greece, and Japan do however show good correlation and make interpretations on global climate zonation possible. At least they show the same trends in timing, although their amplitudes may differ. Yet, for all these records from different environments and geotectonic type regions, identification of local characteristics and effects is necessary before large-scale correlation may be applied, i.e. they should be corrected for local and regional controls on their sedimentation.

[b] Land-sea palaeoclimatic event correlation

Whereas global ice-volume fluctuations in the constant subaquatic and isolated pelagic oceanic environment can be inferred as the only variable quantity of climatic change, the dynamic interplay of climate and regional aspects in the terrestrial environments complicates such a straightforward connection. Land-based palaeoclimatic reconstruction and correlation is facilitated by bringing in an hierarchy in spatial and temporal scale of analysis related to the different depositional environments.

Likewise land/sea correlation of appropriate climate type events interpreted from the depositional sequences is best achieved at two scale levels:

- Matching of evidence of (4th order climato-cyclic) events of global significance that are inferred from the wide-spread unconformity-bounded genetic sequences. The large-scale deposition-

al units, as well as unconformities, from the continent then are fixed to particular time intervals in the global marine isotope chronology giving them a semi-absolute calibration status. Matching thus primarily concerns the global climato-cyclic events i.e. the timing of the glaciations and associated periglacial deserts in Northwest and Central Europe. This implies, for example, that the classical North European and Alpine glacial stages only represent the most extreme (glaciation) maxima in the oceanic isotope record whereas the marine transgressions most likely correspond to the (deglaciation) peaks following the so-called terminations[13]. Their matching with the marine framework can be used for underpinning the chronostratigraphical positions of the sequences from depositional (sub-) environments and unconformities which are more dependent on local and regional controls.
- Matching of palaeoclimatic evidence preserved in small-scale sequences and soil complexes in order to bridge the gaps between two subsequent global-scale events. Subsequently, local evidence embedded in this European glaciation model, for example, periods of forest vegetation from lacustrine records, is matched with the different oscillations succeeding each glaciation maximum in the marine isotope curve. Notwithstanding increased biological activity and diversity providing additional stratigraphical means, spatial and temporal correlation of this independent (often fine-scaled) information cannot be achieved without integration of the large-scale phenomena keeping pace with the marine oxygen isotope sequence.

How the marine isotope stages and their boundary levels correspond to the terrestrial units and their interpreted palaeoclimatic events in mid-latitude Europe will remain undiscussed until *chapter 6*.

2.6 Procedures and terminology applicable to large-scale interpretation and correlation

2.6.1 Unconformity-bounded stratigraphy: subdivision and terminology

Hiatuses form a substantial part of the Pleistocene continental record. They are indicated by numerous surfaces of erosion[14] or non-deposition bounding the sequence geometries. Together with other kinds of hiatuses in the stratigraphical succession such as interruptions in the faunal succession they are commonly termed *unconformities* (Schloss 1963, Mitchum, Vail and Thomson 1977, Emery and Myers 1996).
Subdivision of unconformity-bounded units have long been undervalued as a stratigraphical tool[15]. Because of their diachronous character they were considered of minor importance than the conventional chronostratigraphy (Hedberg (*ed.*) 1976), where time boundaries were regarded synchronous surfaces and fixed to one point in a type section. So, the issue of unconformity-bounded units has long remained inactual and informal. A re-appraisal took place during the 1970s (e.g. Hancock 1977). In the North American Stratigraphic Code (1983) they were formally termed allostratigraphical units.

Units primarily recognised on the basis of bounding unconformities can be used at all scales and levels, from the level of member to that of group. They are thus most practical to serve the precondition of large-scale applicability and may constitute a supplementary (independent) frame next to litho-, bio-, soil-, etc.- (non-interpretive) stratigraphical means. In the last edition of the International Stratigraphic Guide (Salvador (ed.) 1994) they are recognised for the first time as a formal component of stratigraphical correlation.

Basic unconformity-bounded units are termed *synthems* (*cf.* Salvador (ed.) 1994). In many cases they largely correspond to the existing national lithostratigraphical formations. Just as most of the lithostratigraphical codes contain lithogenetic information, synthems also record the succession of depositional environments in the type regions, which by interpretation of the successive facies and intermediate breaks are divided into depositional sequences. Since the major hiatal breaks in the successions also contain evidence of genetic and causal origins they are the (virtual) counterparts of the depositional stratigraphical units between and documenting post-depositional features and reworking of land surfaces.

Deep-sea sediments, apparently displaying continuous deposition in one environment, can be considered one synthem. This is obviously not the case on the continent since the abundance of subaerial and erosional bounding surfaces indicate depositional interruptions and changes of environment. In the localised terrestrial records, many lithostratigraphical units are by their nature bounded by unconformities and can therefore easily be converted into synthems. In first instance, major regional erosional/non-depositional surfaces that can be identified and followed over long distances are considered. These involve unconformities seen as *facies dislocations*[16] due to:
- (Sub-)glacial erosion and accumulation,
- Fluvial incision and aggradation,
- Subaerial exposure (weathering and soil formation) and
- Marine (and lacustrine) transgressional and regressional phases and low - and high stand tracts.

They can be regarded as valid correlation surfaces for dividing the stratigraphy. The recognition of unconformable boundaries of sequences from core or outcrop datasets, however, is not always easy and evidence for erosion and exposure must be sought then from other evidence. A lot of unconformities are of restricted areal extent and not useful at regional scales. Some exceptions are volcanic units, changes in lake sequences and the occurrence of secondary carbonates, providing useful marker horizons and beds.

The deeply-incised valleys of the Fennoscandian Elsterian glaciation are good examples of (glacial) *erosion surfaces* reflecting a major erosion phase during the glaciation maximum. Morphological features, such as river terraces in upstream regions are also bounded by erosional unconformities and can be assigned a synthem, although they may contain internal unconformities. Incised valleys in downstream river sections are defined as entrenched fluvial systems that extend their channels in response to a fall in sea-level and erode into underlying strata (Van Wagoner *et al.* 1990). Loess and slope deposits covering river terrace sediments may be attributed to different unconformity-bounded units. Their upper boundaries are commonly formed by subaerial unconformities that have been exposed to weathering and soil formation like the present-day surface. Unconformities that lack evidence of exposure, such as reddening or palaeosols, which have been removed by subsequent erosion, are called *E/T*[17] *surfaces* (Emery and Myers 1996). The bounding surfaces of the loess units may be associated with the transitions of cold periglacial to warm conditions or reversed. These transitions are possibly shorter in time duration than the time of duration of loess deposition or of the soil formation.
In the marine realm *ravinement surfaces* are surfaces of transgres-

sive erosion (Stamp 1921). *Marine flooding surfaces* are surfaces separating younger from older strata across which there is evidence of an upward increase in water depth.

2.6.2 (Genetic) sequence stratigraphy: subdivision and terminology

In the next interpretive phase, groups of strata are distinguished as high-rank sedimentary units whose unconformity-bounded sequences are genetically related to a variety of tectonic and climatic settings in a type region. These sedimentary groupings (discussed in *section 3.2*) are related to the major depositional environments: marine, glacial, fluvial, lacustrine, subaerial (including aeolian), and some local, highly specific sub-environments such as springs, caves, karst, volcanic craters and slopes. Their geographical distribution depends on latitude, (palaeo-)topography, the subsurface geology and the tectonic structure.

Sequence stratigraphy is initially mainly applied to marine depositional systems in large sedimentary basins, and distinguishes between sedimentary units that can be related to a change in sea-level (Mitchum *et al.* 1977, Nummedal *et al.* 1987; Miall 1990; 1997). The recognition that part of the sedimentary succession may be dominated by distinctive stratigraphical events, such as wide-spread marker beds or discontinuities caused by glacio-eustatic sea-level change, is used to distinguish between *sedimentary sequences*[18] which have extended laterally through time. These distinctive events may be both climatically and tectonically controlled. In particular high-resolution shallow seismic data have contributed to the development of detailed case histories of sedimentary basins (Emery & Myers 1996), mainly used in hydrocarbon reservoir studies.

Applying sequence stratigraphy to terrestrial depositional systems in continental large- and small-scale basins is not as straightforward because of the different data acquisition (continuous seismic profiles generally are not available) and geological processes involved. Not only relative sea-level should be considered as a parameter of spatial and temporal change of basin geometries and fills but a variety of factors: graded river profiles, lake levels, ice-sheet limits, isotherms (for example of frost action) and isohyets. This is unfeasible at the moment and the applicability of sequence stratigraphy for environments other than marine settings is still in its infancy (Emery and Myers 1996). Although facies analysis of the terrestrial environments into facies models and depositional systems probably is better suited to the term *environmental stratigraphy* (*cf.* Walker (*ed.*) 1980), relationships to stratigraphical events are not involved.

Nevertheless, the use of the term sequence, in a restricted sense meaning a (cyclic) stratigraphical unit bounded by subaerial and erosional unconformities, is very practical. And the definition of the terms 'depositional episode' (Frazier 1974) or 'genetic stratigraphical sequence'[19] (Galloway 1989) links with terrestrial sedimentary units that record significant time intervals associated with climate-driven events such glacial expansions, periglacial subaerial (loess) deposition, or tectonically-induced fluvial aggradation phases.

Alhough aims of subdivision may correspond, temporal scale of research however differs. When applying the terms mentioned above to the Pleistocene record of climatic fluctuations in sedimentary basin analysis, spanning at most 2.6 millions of years, they comprise relatively high order scale cycles which should probably be distinguished at a parasequence level only, representing just an oscillation in an otherwise long-term trend of a sequence. Nevertheless, it is believed permissible for the present purpose to distinguish the wide-spread terrestrial sedimentary units deposited by the relatively short-term Quaternary climatic 4th order cycles at a sequence level. Each terrestrial genetic sequence unit then is stratigraphically related to a depositional cycle as a preserved product of a major palaeoclimatic event.

2.6.3 Event stratigraphy: subdivision and terminology

The term *event stratigraphy* (Ager 1973, NASC 1983, Salvador (*ed.*) 1994) is applied to the correlation of interpreted geological events rather than the lithological characteristics of sediments. Initially it was referred to short-term, catastrophic events like floods, storms and volcanic eruptions often leaving synchronous marker beds. Gradually, also infrequent or extreme longer-term 'events', but of the 5th order, have become included like changes in Pleistocene climate, in tectonic trends and in global sea-level which are responsible for wide-spread cyclicity in the sedimentary record.

Such palaeoclimatic events, inferred from (cyclic) deposits called *depositional sequences* of which some may be grouped into *megasequences*, may be of global scale, such as glaciations, periglacial deserts, sea-level highstands, or may only indicate local- or regional-scale ecological events, for example forest vegetation climaxes. This differentiation and nomenclature may avoid the common confusion invoked by the traditional climatostratigraphical schemes classifying only glacials and interglacials.

In a similar way, sediment bodies in different type areas in Europe are interpreted as products of periodic depositional and erosional events which are related to climatically- and (neo)tectonically-induced changes, such as sea-level highstands, ice-sheet expansion, permafrost distribution, periglacial loess deposition, biological productivity, vegetation climaxes and (palaeo)hydrology (= fluvial response and mode). As already mentioned, such events may have considerable chronostratigraphical significance and may therefore also provide a supplementary basis for the stratigraphical subdivision of the terrestrial Pleistocene sequence. Besides, this approach, which combines facies analysis, depositional origin and sequence stratigraphy methodologies can be used as an overall framework to cover and structure the existing regional stratigraphical systems and terminologies and can be used as a link with the ocean record.

Thus, we are not correlating the deposits themselves, nor the fossils, but the inferred events (*cf.* Ager 1981) as evidence of depositional cycles in the predominantly erosional Pleistocene terrestrial environments. Since most Pleistocene events are climatically-driven (palaeoclimatic events), global and regional signals can be compared. On a large scale, these correlations may be very gross and should be confirmed by independent evidence. For each region corrections for differential uplift and subsidence patterns should be included, co-controlling sediment supply, accommodation space and base levels.

The nomenclature of depositional and interpreted climatic cycles within different sequences (and for the MIS) is commonly designated in capitals of alphabetic order or in numerical order: A, B, C or 1, 2, 3 and so on for older cycles. An example from Europe are the glacial cycles distinguished by Kukla (1970) in the loess/palaeosol sections in Slovakia and Austria. They are shown in *Figure 3.2*.

[1] *Correlation of stratigraphical units is dealt with in section 2.1.4.*

[2] *The latter does for that matter not hold for the zonation in fossil assemblages, which is non-hierarchical.*

[3] *That is beyond the C14 dating limit of 40-50 ka.*

[4] *And holostratotype.*

[5] *Lithostratigraphical and biostratigraphical units are said to be homotaxial when they have a similar order of arrangement in different localities but are not necessarily contemporaneous.*

[6] *Recently, the stratigraphy of the Netherlands has been reviewed (Weerts* et al. *2003, Westerhoff* et al. *.2003) and a lithostratigraphical subdivision is used next to the interpretative 'old' units.*

[7] *When of global significance they are defined as a Global Stratotype Section and Point (GSSP).*

[8] *The reason for this, its brief duration and different scale of resolution, was only realised later after the introduction of physical methods for absolute dating in the twentieth century.*

[9] *That is beyond the limit of radiocarbon dating which is about 40-50 ka ago.*

[10] *cf. Steno's principle of superposition, already formulated in 1669.*

[11] *Perhaps with the exception of the pollen-containing marine cores off Portugal which have been correlated for MIS 5 (Sánchez-Goni et al. 1999) and MIS 11 (Desprat et al. 2005).*

[12] *A markline is the boundary between primary aeolian loess units, each representing a glacial cycle, and the decalcified B-horizon of the overlying soil.*

[13] *See also section 6.3.1.*

[14] *Angular unconformities, disconformities.*

[15] *Although the principal units of the chronostratigraphical scale originally were recognised as suites of rocks bounded by major lithological or faunal changes, breaks, unconformities, or discontinuities (section 2.2.1).*

[16] *A facies dislocation is a surface where rocks of a shallower facies rest directly on rocks of a significantly deeper facies. The term orginates from sequence stratigraphy on seismic and core data from marine and fluvial sediments in sedimentary basins, but can also be applied to other depositional environments. Changes in lithology then are interpreted in terms of natural (gradual) successions in the depositional environment. Anomalies then are facies dislocations, implying for example the development of a subaerial unconformity or a fall in relative sea, lake or base level resulting in erosion and subsequent covering of deposition in another environment.*

[17] *E stands for erosion, T for truncation.*

[18] *A sedimentary or depositional sequence represents a complete cycle of deposition bounded above and below by erosional unconformities (Emery and Myers 1996). Without the preposition depositional, the term sequence is used (and has been used in the previous chapters) in the broad sense of a succession of sediment layers, morphological features, etc.*

[19] *A genetic stratigraphic sequence (Galloway 1989, after the work of Frazier 1974) is defined as a package of sediments recording a significant episode of basin-margin outbuilding and basin filling, bounded by periods of wide-spread basin-margin-flooding. The suggested (upper) cycle boundary then is the maximum flooding surface, which is relatively isochronous.*

Chapter 3

CONTEMPORARY MIDDLE PLEISTOCENE TERRESTRIAL STRATIGRAPHY OF NORTHWEST AND CENTRAL EUROPE; A COMPLEX OF LOCAL STRATIGRAPHIES AND PALAEOCLIMATIC STAGES

3.1 Climatostratigraphical subdivision of the European Pleistocene terrestrial succession

3.1.1 Historical development

Since Pleistocene stratigraphical successions in terrestrial environments are largely governed by climatic fluctuations, as indicated by lithology, structural features, fossils, soils and geomorphology, inferred climate has been used in Europe for over a century[1] as the most suitable basis for the distinction and subdivision of the Pleistocene strata and time.

The first widely-used Pleistocene stratigraphical scheme in Europe was the fourfold glaciation paradigm as initially developed by Penck & Brückner (1901-1909) for the northern Alps and mainly based on morphostratigraphical criteria. Glaciofluvial outwash terraces in the Bavarian type area were related to moraines and glacial deposits of the Alpine piedmont glaciers and used as units representing the Würm, Riss, Mindel and Günz glacial stages. Morphostratigraphical criteria were also applied to the area of northern Europe subject to ice-sheet glaciation from Fennoscandia (e.g. Penck 1879, Keilhack 1896, 1926; Woldstedt 1929, 1954). The type units of the glacial stages here, named from young to old Weichsel, Saale and Elster respectively, were originally recognised from the end-moraine belts crossing the Northwest and Central European lowlands. Another classification is related to the British ice-sheet expansions where also three major glacial stages (Devensian, Wolstonian[2] and Anglian) are well represented (King 1955, West 1963).
Unlike the Alpine region, the distribution and superposition of glacial sequences and landforms in many areas in northern Europe could be stratigraphically related to marine, limnic, fluvial and organic interglacial deposits. The latter generally contain biostratigraphical information as well as biological evidence of warmer climate conditions. Following the work of Jessen and Milthers (1928) in Denmark, palynology, together with palaezoology, became an important stratigraphical tool to define interglacials s.s. (and interstadials) as principal bio- and climatostratigraphical units and to correlate these units over wide areas in northern Europe.

The main difficulties in the climatostratigraphical interpretation of the Pleistocene sequences were the relative chronology in general and the lack of objective correlation means between the glacial sequences in northern Europe and those in the Alps. Newly developed concepts, dating methods and increased data availability in the 1950s and 1960s gradually made clear that the Alpine glacial scheme[3] could not be adopted continent-wide and became a 'strait-jacket'. In the absence of such an overall framework, a complex of local stratigraphies evolved in Europe. Based on the local litho- and biostratigraphical frameworks to which genetic and causal aspects have been built in during the interpretative phase, each country or state developed its own subdivision and nomenclature of the Pleistocene Series/Epoch into palaeoclimatic stages. By counting down the units from the top, each scheme involved an arbitrary subdivision into interpreted glacial stages, defined mainly from lithological and structural evidence, and intermediate interglacial stages, generally identified from biotic palaeoclimatic indicators. Although criteria for the identification and definition of the climatostratigraphical units and their boundaries differed from country to country, the approach was to use them as a basis for interregional correlation, as advocated by Van der Vlerk (1953) among others. The most comprehensive local series of cold and temperate stages, based on superposition and in particular palaeobotanical data, are from the Netherlands, as part of the southern North Sea sedimentary basin (Zagwijn 1975).

The inherent deficiency of the composite local schemes established in the formerly glaciated areas became more and more apparent when in the 1970s evidence from extraglacial areas became available. Loess/palaeosol sequences overlying river terrace deposits from Central Europe (Červený Kopec: Kukla 1970, 1975) and long pollen records of lake sediments (Tenaghi Philippon in Greece: Wijmstra 1969, Van der Wiel and Wijmstra 1976) were hardly compatible in terms of the numbers of glacials and interglacials. Also evidence from Poland (e.g. Rozycki 1978) and the Russian Plain (e.g. Velichko 1984, 1990) did not fit easily into the classical models.
Moreover, in the light of the virtually continuous record of the Quaternary climatic history from the deep-ocean sediments (first published by Shackleton & Opdyke 1973), which demonstrates at least 11 major global cycles of glaciation in the last million years, it was shown that the frequency of glacial and intervening interglacial periods was dramatically underestimated. The vast amount of information from ocean and ice-core records, the enormous advances in geochronological techniques and the re-assessment of traditional concepts in most disciplines over the last three decades brought about continual appraisals and re-evaluations of the local and regional stratigraphical schemes and terminology. An overview of regional schemes of subdivision based on interpreted climate is shown in *Figure 3.1*.

Nevertheless, terrestrial subdivision remained constrained by stratigraphical relationships and low resolution chrono-markers. To tackle the chrono- and climatostratigraphical problems onshore, further refinement was then sought in comparison and matching of the local and regional Pleistocene evidence with the ocean and ice-core chronostratigraphies. Since the inferred palaeoclimatic stages have to fit somehow with parts of the marine relative chronological sequence, many stratigraphers in the last three decades have actually proposed and compiled MIS correlation schemes (a.o. Kukla 1975 and 1977, Bowen 1978, Sibrava *et al.* 1986, De Jong 1988, Ehlers, Gibbard & Rose 1991, Ehlers 1997, Vandenberghe 2000).
Kukla (1969, 1970, 1975) was the first who convincingly matched loess/palaeosol cycles from Slovakia and Austria (*Fig. 3.2*) with the glacial cycles of the marine isotope record for which later the long loess records from China became available (Kukla 1987, Kukla and An 1989). So far eight completed loess accumulation cycles are recognised within the Brunhes normal Chron. These

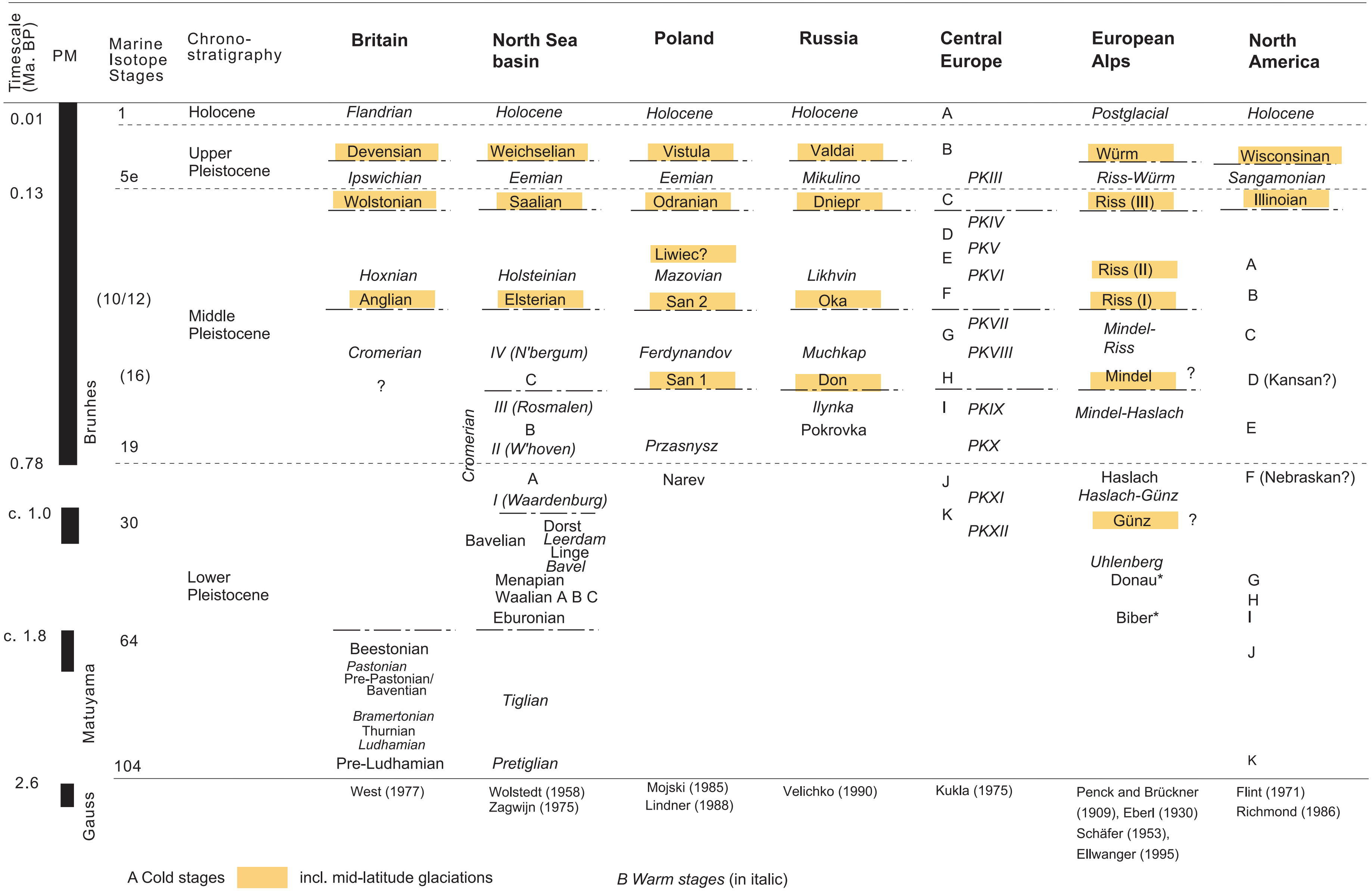


Figure 3.1 Overview of the terrestrial Quaternary (climato-)stratigraphical schemes and terminology for Europe and North America in relation to the global chronology.

cycles coincide with the 4th order glacial cycles of about 100 ka duration in the oceanic record. Up to now only the last two glacial cycles can be accurately correlated with the northern and central European mid-latitude glaciations: the Fennoscandian Weichselian / British Devensian / Alpine Würmian ice-sheet expansions and the Fennoscandian Saalian ice-sheet expansion. On a local scale, matching of pollen records from lake-core sequences with the ocean record showed similar climate-related trends for the Late Pleistocene, such as La Grande Pile and Les Echets in France (de Beaulieu and Reille 1987), Bispingen-Luhe in Germany (Field *et al.* 1994) and for the Middle Pleistocene, e.g. Tenaghi Philippon in Greece (Mommersteeg *et al*. 1995) and Lac du Bouchet/Praclaux in southern France (de Beaulieu and Reille 1995, Tzedakis *et al*. 1997, de Beaulieu *et al*. 2001).

Global matching was mostly achieved from a specific disciplinary or regional point of view and by 'counting down or up' within conventional frameworks. With the exception of Kukla's loess cycle concept, scholars did not work in a systematic way by defining unambiguous regional unit boundaries nor applied a set of large-scale correlation criteria before matching with the MIS. It is true that the use of climatic terms for the main building blocks of the glacial models met the aim of large-scale interpretation, i.e. 'the spatial reconstruction of past climate and landscapes at large (4th order) time scales'. It does, however, not satisfy for local, often temperature-related inferences from the intermediate interglacial sequences. The character, distribution and preservation of the latter are also controlled by regional (bio)geographical, geological and geotectonic variability, reflecting various short-time cyclic events.

3.1.2 Climatostratigraphical subdivision in perspective

Unfortunately, the European type localities and stratigraphical systems for at least the Early and Middle Pleistocene do not appear to be easily comparable nor synchronous (Turner 1975, Bowen 1978). In general, there is little dispute about the relative position of the dominant glacial and periglacial aeolian sedimentary units within the formerly glaciated or the non-glaciated type areas. Interregional chronological correlation of these major cold climate-driven sequences, however, is hampered by often inconsistently interpreted climatic signatures and time durations from the sequences themselves. It may also be interpreted from the scattered local, intermediate non-glacial successions, in particular from lake deposits and soil complexes comprising interbedded organic-rich horizons. Although the palaeobotanical and faunal evidence from these intermediate non-glacial deposits has particularly provided much climatic and environmental detail within the local stratigraphies, the spatial and temporal resolution of biostratigraphy and pedostratigraphy is generally limited. The fossil contents of the widely-spaced and predominantly incomplete sedimentary records show geographically-related anomalies. Moreover, most fossil groups lack substantial evolutionary change (with the exception of voles). And despite the migrations over long distances, there are similarities in species assemblages during subsequent climate stages which pose bio-correlative problems. Thus, for much of the Middle Pleistocene there are too many uncertainties for correlations to rely on palynology, pedology or other disciplines alone (*cf.* Turner 1996).

The main reasons for the unsatisfactory way in which the climatostratigraphical subdivision of the European Pleistocene has been documented, have been:

- Local (mis)interpretation of the interglacial, interstadial and glacial signatures from the sedimentary and fossil records within the geographically widely-spaced successions,
- Interregional miscorrelation of these,
- Variously and broadly defined unit boundaries.

The interpreted climatostratigraphical units are a major source of stratigraphical confusion on the continent. They likewise furnish difficulties to achieve an overall picture of the past climate. Attempts to correlate the climate-based units from one region to another have led to many discrepancies. The loess/palaeosol sequences in the extraglacial areas show more climatic cycles than the glacial sequences. Moreover, there is the problem of drawing boundaries of climate change. The interpreted climatostratigraphical units principally refer to local temperature and moisture conditions during relatively short periods of deposition in different glacial or non-glacial environments. Many of them only indirectly indicate climatically-induced events of global significance. Although climatostratigraphical units are intended to refer to climatic events as a cause for deposition, problems arise when, for example, every superimposed till in a glacial sequence is interpreted as a product of a discrete glaciation or when every organic stratum should represent an interglacial stage.

Thus, the synthetic character of the local and regional climatostratigraphical units make them inadequate for interregional correlation. Too many aspects of climatic history on the continents remain constrained by available local-scale multidisciplinary evidence and ages (Turner 1996). Regional long-term controls such as endogenic tectonics[4] may also be of importance in affecting the depositional systems and combine in different ways with shorter term exogenic climate influence in different depositional systems.

3.1.3 Persistent terminology

Climate-based units are still the principal units of conventional Pleistocene stratigraphy. Traditional terms like 'glacials'/'glacial stages' (as well as their subdivisions into 'stadials'/ 'stades' and 'interstadials'/'interstades') and 'interglacials'/'interglacial stages' have been used worldwide and remain very persistent[5]. However, these terms are actually only suitable within formerly glaciated areas. There is no clarity in the criteria by which they should be identified and defined elsewhere. Moreover, even within the glaciated regions, boundaries were identified and defined on the basis of different evidence and criteria. Furthermore, the nature of several deposits hampers unequivocal climatic interpretations to be made. Nonetheless, climatostratigraphical units were accorded formal status for a while, e.g. the geologic-climate units in the American Code (1961), but this was regarded unfeasible in the end.

Glacials/glacial stages exclusively refer to the glaciations of mid-latitude Europe as indicated by glacial deposits and landforms, for example the Weichselian, Saalian and Elsterian glaciations.

Interglacials/interglacial stages were initially used to identify erosional time units between the Alpine glacial stages, i.e. events not represented by deposits. Palaeobotanical evidence from Northwest European lake, mire and coastal marine records initiated the definition of interglacials, and interstadials, as forested periods. Following the proposal by Jessen and Milthers (1928), interglacials were defined as particular types of non-glacial conditions, as indicated by vegetational changes. Later, they also became equated with marine transgressions, periods of soil formation and other features related to relatively warm climate conditions.

In order to avoid confusion and ambiguity over nomenclature and definitions of palaeoclimatic units, the use of above-mentioned

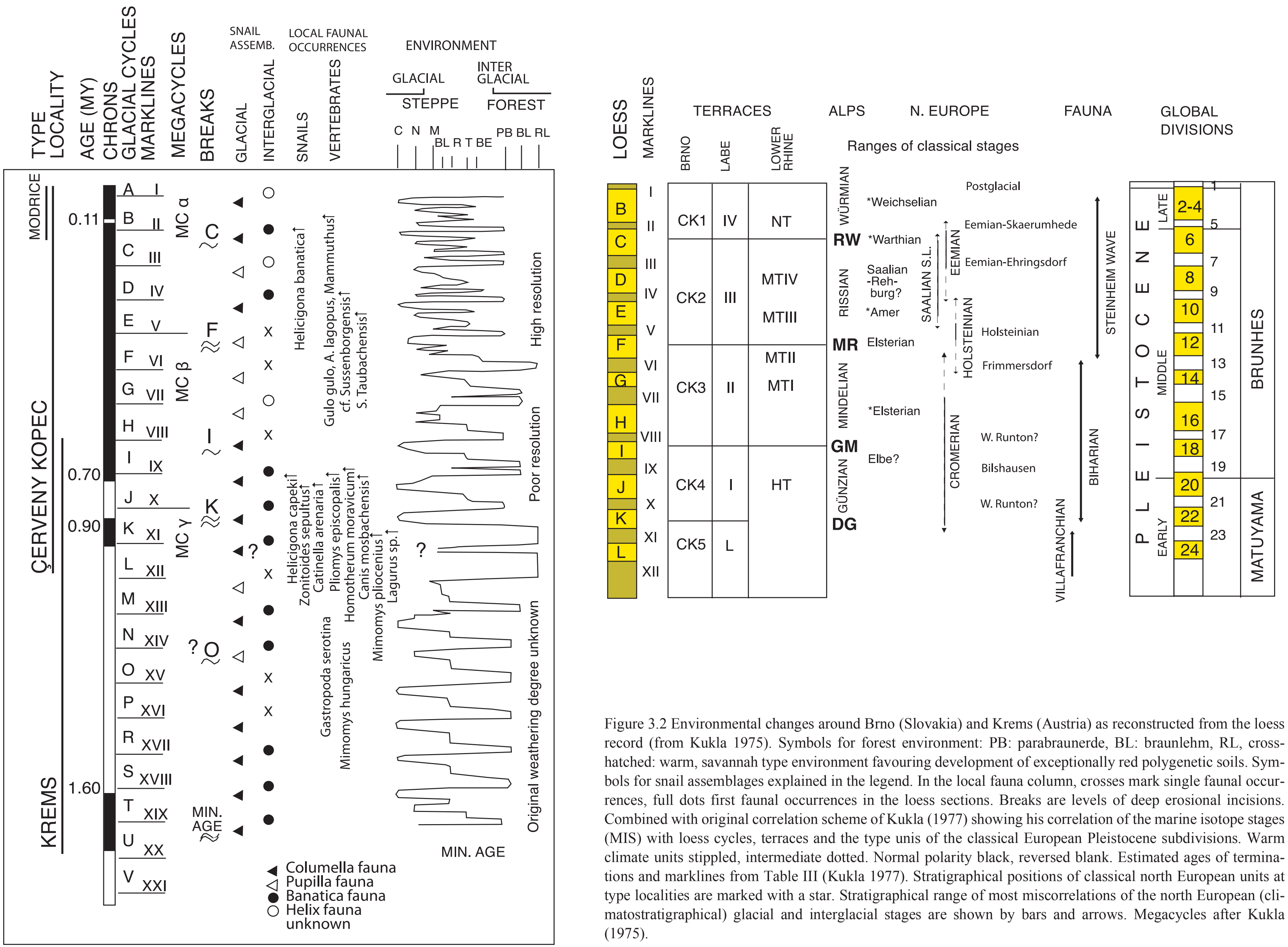


Figure 3.2 Environmental changes around Brno (Slovakia) and Krems (Austria) as reconstructed from the loess record (from Kukla 1975). Symbols for forest environment: PB: parabraunerde, BL: braunlehm, RL, cross-hatched: warm, savannah type environment favouring development of exceptionally red polygenetic soils. Symbols for snail assemblages explained in the legend. In the local fauna column, crosses mark single faunal occurrences, full dots first faunal occurrences in the loess sections. Breaks are levels of deep erosional incisions. Combined with original correlation scheme of Kukla (1977) showing his correlation of the marine isotope stages (MIS) with loess cycles, terraces and the type unis of the classical European Pleistocene subdivisions. Warm climate units stippled, intermediate dotted. Normal polarity black, reversed blank. Estimated ages of terminations and marklines from Table III (Kukla 1977). Stratigraphical positions of classical north European units at type localities are marked with a star. Stratigraphical range of most miscorrelations of the north European (climatostratigraphical) glacial and interglacial stages are shown by bars and arrows. Megacycles after Kukla (1975).

classical terms as overall climatic periods of cold (peri-)glacial conditions versus warm intervening non-glacial conditions is discouraged here. They will be as much as possible used and referred to in this thesis in their original sense and validity for the formerly glaciated regions.

A more meaningful, and widely applicable, basis for climatic subdivision on the continent is to distinguish between relatively cold stages and warm stages (*cf.* Suggate and West 1969, West 1988). These broad units of climatic change are based on local climate type interpretations[6] and compared to the present-day climate zonation of the mid-latitudes[7].

Warm or warm-temperate stages are periods characterised by forest vegetation, high sea-level stands and soil formation of substantial length comparable to the present day. In this respect they may be used as a synonym for the original 'interglacial stages' as determined from vegetational changes (Jessen & Milthers 1928). And the Eemian and Holsteinian warm stages refer to the marine transgressions in the North Sea, as well as the deciduous forest vegetations in the lake records on the continent.

Cold stages comprise all (negative) anomalies to the present-day climate zonation. They are therefore generally complex in nature and represent time periods of climatic deterioration with permafrost occurrence, tundra and steppe vegetation type, lowered sea-levels and one or more periods of ice-sheet expansion. Thus 'glaciations' or 'glacial stages' are included in the cold stages and comprise the periods of ice-sheet expansion during 'stadials'. Additionally there may be interruptions by short forested periods ('interstadials' or boreal substages) within the cold stage.

Climate type anomalies from palaeotemperature estimates can be applied to both glacial and extraglacial areas and can be recognised from deposits and structures in different depositional environments, from biota (pollen assemblages, insects) as well as from palaeosols and landforms (e.g. push moraines). Furthermore, estimates of precipitation or moisture conditions (humid/dry) can be added. Cold and warm climatic stages or periods are thus quite flexible, geographically dependent regional units, signifying several geological events, deposits or features. Both general terms will be used in discussing and reviewing the Middle Pleistocene climatic sequence in this thesis. Their informal status implies that their initial letter should not be capitalised, unless the term stage is used to refer to formal chronostratigraphical units at the (sub-)stage level, e.g. the Saalian Stage. *Figure 3.3* shows the regional subdivision of climatic stages valid for the Northwest European lowlands in relation to the chronostratigraphy.

3.1.4 Climatostratigraphy and chronostratigraphy

Climatostratigraphical units were thought to offer foundations for chronostratigraphical subdivision of the Pleistocene sequences and for interregional correlation. However, in view of the complex and heterogeneous nature of its succession, together with its brief age, the matching of locally and regionally known stratigraphical units appeared to be a correlative obstacle to chronostratigraphical subdivision. Supposed time correspondences between the climatic stages were based on the correlation of lithological characteristics, palaeontological and palynological data and other evidence like morphological and pedological features. The inherently defective and 'floating'[8] local and regional chronostratigraphical models, however, comprise few geochronological control points and many

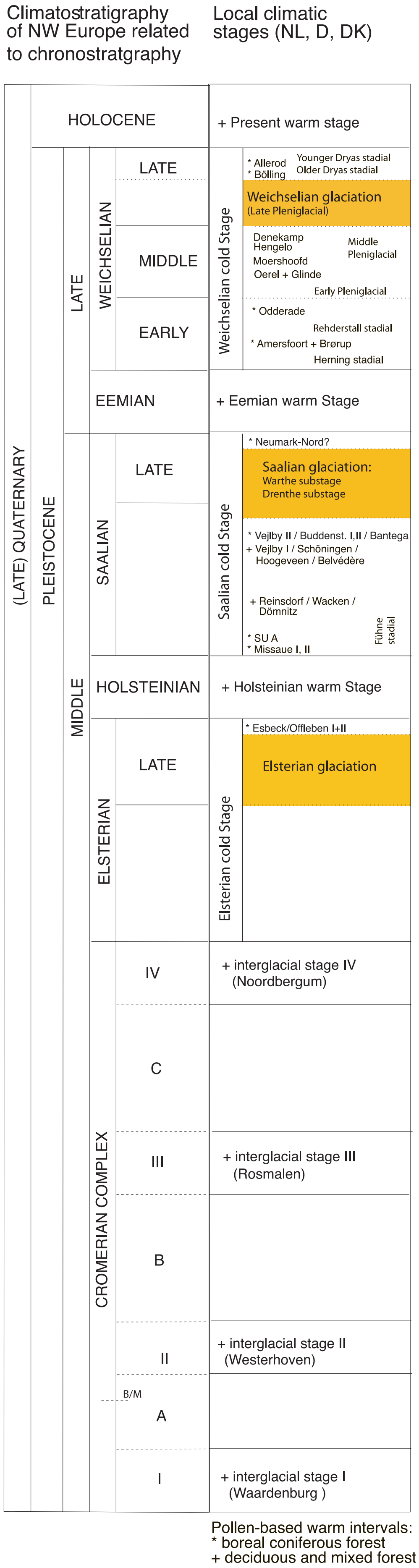


Figure 3.3 Subdivision of the Middle Pleistocene in Northwest Europe based on interpreted cold and warm climatic stages (compiled from different sources).

diachronous hiatal breaks as missing links of unknown duration. Notwithstanding the practical merits of classifying local sequences into climate episode units, they should not be adopted as chronostratigraphical stages (and hence not geochronological ages) applicable on a continental scale. Climate-based units, like the conventional stratigraphical units from which they are established, are equally time-transgressive, geographically and temporally restricted fragments. Consequently, they do not have an adequate chronostratigraphical definition, that is based on unit- or boundary stratotypes within a continuous sequence and with time-parallel boundaries. A stage or substage rank implies time correlation which is neither true for cold nor for warm stages in northern Europe. Moreover, the use of various criteria for their boundaries is inconsistent and implies the existence of gaps (and in some cases, overlaps) which is generally not shown in the palaeoclimatic tables and curves. Major erosional and subaerial unconformities filling the gaps between phases of sedimentation may span tens or hundreds of thousands years. They therefore form a substantial, but virtual, part of the chronostratigraphy in the different European type regions (Kukla 1975, Bowen 1978). A better appreciation of their relevance is emphasised and substantiated in the stratigraphical procedures followed in *section 2.5*.

The basic European glacial models may be regarded as outdated. Although intrinsicely different in nature, they are only rough structures when compared to the interglacial-glacial cycles in the oceanic record. Kukla already concluded in 1977 ‘that it is urgently recommended to abandon the classical terminology in all interregional correlations and to base the chronostratigraphical subdivision of the Pleistocene on the (^{18}O-record of deep-sea sediments’ that showed eight, instead of four, glacial cycles during the Brunhes normal Chron. Because all terrestrial sequences contain actual and potential hiatuses, Bowen (1978) also proposed that the deep-sea cores should be used as a standard. While the temptations of direct land-sea correlations are large, the replacement of locally established terrestrial scales has never been achieved in a formal or systematical way. There are many principal objections and practical limitations involved, as noted by Gibbard and West (2000). They recommend the separation and retention of regional chronostratigraphies for each sequence-type, and that these should be correlated using event-based stratigraphy where possible. Thus, in the absence of a valid European framework, subsidiary classifications are required that better represent the terrestrial Pleistocene record and that potentially offer opportunities to correlate with the marine isotope stratigraphy.

3.1.5 Chronostratigraphical boundaries of the Middle Pleistocene subseries

Internal dating of the Middle Pleistocene succession in the Northwest and Central European type regions is primarily relative and based on superposition and correlation of preserved depositional (lithostratigraphical) units and their biostratigraphy, using palynological and various palaeozoological zonations. Geochronometric and geomagnetic dating methods, developed since the 1950s, have to some extent proved valuable supplementary means on the chronostratigraphical position of deposits (see also *section 3.4*). The resolution of these methods, however, decreases with time. The radiocarbon method, established by Libby (1955), provided a sound basis for dating the last 40,000 to 50,000 years. Dating techniques such as K/Ar, Ar/Ar, TL and OSL, U-series and ESR[9] yield ages up to 300-400 ka, or even more, for suitable sediments and fossils, but are not very reliable yet and still in development. Consequently, the discontinuous and genetically diverse Middle, and likewise Early, Pleistocene terrestrial subseries have a low resolution classification[10]. In fact only the lower and upper boundaries can be accurately defined:

The lower boundary of the Middle Pleistocene is proposed at the first sedimentary units where palaeomagnetic dating of the sediments show normal (Brunhes) geomagnetic polarity (Richmond 1996). A lower dating limit of about 780.000 years[11] ago then can be set as a maximum age which corresponds to MIS 19.

Based on different criteria the upper boundary of the Middle Pleistocene on land is defined at the beginning of the last interglacial/glacial cycle. This in practice appears to be a diffuse non-synchronous boundary. The transition of glacial and subaerial periglacial sequences, related to the penultimate completed glacial cycle (C), to the last non-glacial (Eemian) sedimentary cycle of marine, lacustrine and fluvial origin, or to soil formation (starting with decalcification) or to forest vegetation, is represented by different starting points in the time interval between the MIS 6 global ice-volume maximum and MIS 5e global ice-volume minimum, i.e the deglaciation. The Middle/Late Pleistocene boundary is set at the transition of MIS 6 and 5e for which the midpoint at 128 ka (‘termination II’) has been chosen arbitrarily as stage boundary (Broecker and Van Donk 1970, Gibbard 2002). Recently the Amsterdam-Terminal borehole (Van Leeuwen *et al.* 2000) has been proposed as the Eemian boundary stratotype for Northwest Europe (Gibbard 2003).

3.2 Material building blocks of the Northwest and Central European Pleistocene stratigraphy

The shallow subsurface of Northwest and Central Europe is one of the best geologically investigated areas worldwide. Material evidence of unlithified Pleistocene deposits from numerous field research localities, such as open-air sections and boreholes, have been described and subdivided into local, regional and national classification systems. The factual units structuring the local stratigraphies are of a lithostratigraphical, biostratigraphical and morphostratigraphical type in which (litho)genetic aspects play an important role. They do represent many different environments having repeatedly coexisted in Pleistocene time. This section reviews the building blocks of the local and regional stratigraphies of this part of Europe and the relationship between the stratigraphical sequences at one locality to those at another.

The basic sedimentary components building and contributing in different ways to the local and regional stratigraphies are:

- Sediments generated in glacial depositional environments,
- Sediments generated in subaerial periglacial depositional environments,
- Marine coastal and shallow sea sediments,
- Fluvial and deltaic sediments produced by the large river systems,
- Sediments deposited in lakes, mires and bogs.

These categories represent the dominant depositional systems which form the main building blocks from which the regional Quaternary stratigraphies of Northwest and Central Europe are constructed. Since most formations in the different European stratigraphical systems include lithogenetic criteria, they generally correspond to one of the five categories. With the exception of the lacustrine deposits, the sediments of the other categories have dispersals that can be mapped over large areas. They largely corre-

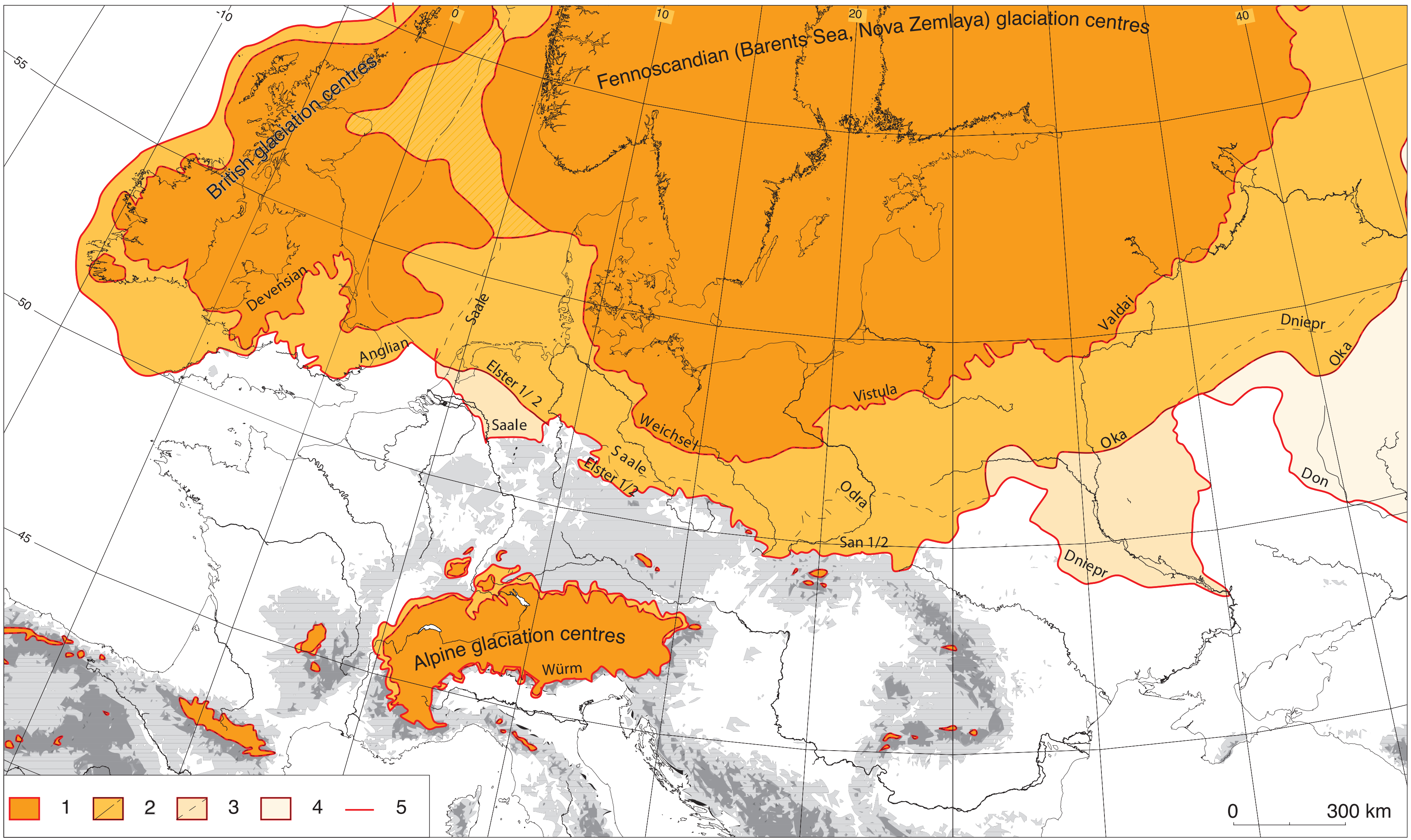


Figure 3.4 Distribution of Pleistocene glacial sequences in Northwest and Central Europe (from ‘International Quaternary Map of Europe’, UN/BGR 1965-1995). 1. Extent of Weichselian, Devensian and Würmian glacial sequences, 2 Extent of Elsterian, Anglian and Mindelian glaciation limits, 3. Extent of Saalian and Rissian (I) glaciation limits, 4, ice-free area during the Fennoscandian glacial cycle B (Weichselian, Devensian), 5. maximum limits of the Pleistocene glaciations.

spond to the legend units of the 1:2.5 million scale 'International Quaternary Map of Europe' (UN/BGR 1965-1995) from which the distribution maps in *Figures 3.4* up to *3.8* have been compiled.

In the next sections the litho- and biofacies characteristics and stratigraphical significance of the categories will be discussed in relation to depositional processes, climatic change and regional tectonic effects that controlled their formation. Emphasis is put on glacial and periglacial sedimentary sequences since their geometries largely structure the local stratigraphies in the glaciated areas respectively the extraglacial areas in Europe. From both areas compilation schemes are produced, arranged along W-E transects, which are presented and further discussed in *section 4.2*.

3.2.1 Sediments generated in glacial depositional environments

Glacial sequence includes till (glacial diamicton), glaciofluvial sand and gravel, glaciolacustrine and glaciomarine clay, silt and ice-rafted detritus. Tills do not occur beyond areas covered by ice-sheets and glaciers. Glaciofluvial and glaciolacustrine sediments preserved on land areas do not extend far beyond the maximum extend from which they were derived (Boulton 1990). Glaciomarine sediments are laid down beneath and in front of ice-sheets which entered the sea. Also non-glacial sediments which have been glaciotectonically deformed and/or dislocated, and are commonly incorporated in push moraines, may be considered part of the glacial depositional system.

The extent of glacial sediments and landforms in Northwest and Central Europe is shown in *Figure 3.4*. The subdivision of glacial stages in Northwest Europe was formerly based on morphostratigraphical criteria ('Endmoränenstratigraphie' - e.g. Keilhack 1926, Woldstedt 1929 and 1954) but is now based on till stratigraphy. Nonetheless, the classical subdivision of glacial stages (Elsterian, Saalian and Weichselian) is still regarded as valid, although till stratigraphical studies have revealed several phases of glacier advance and retreat within each stage. In eastern Europe (Poland and Russia) this three-fold subdivision may be extended by an older glacial stage (Donian). The Don tills extend far south into the Don basin (Velichko and Faustova 1986).

Because of the strongly erosional effects of ice-sheets, preservation conditions of glacial (and non-glacial) deposits predating the latest glaciation are limited and cause for major unconformities. Most extensive depositional glacial sequences are found in former ice marginal positions where they intervene with fluvial, aeolian and slope sequences of the periglacial zone.

The major sedimentary elements in glacial environments are:

[a] Tills

Till units[12] play an essential role in structuring stratigraphical subdivisions in northern Europe. They were deposited by wide-spread glacial events which were well-integrated on a continent-wide scale. Till units can therefore expect to be correlatable as part of a wide-spread sedimentary product whose properties also vary systematically on a continent-wide scale. Appropriate sedimentological analyses can therefore yield reasonable correlations which permit lateral connectivity to be established between otherwise disconnected exposures. They permit workers to reduce the high degree of uncertainty in stratigraphical reconstructions in an otherwise poorly represented time/space domain such as that shown in *Figure 4.2*. Boulton *et al.* (1997) have argued that tills are generally deposited in a relatively narrow zone close to an ice-sheet margin and that in more proximal zones erosion will dominate. As a consequence, except near to the limit of glaciation, much of a glacial phase will be taken up by erosion and only the last phase of glaciation will be represented by till at any one site. Genetic distinctions between basal or lodgement tills, ablation tills and flow tills are rather irrelevant then. The till unit produced during a simple glacial cycle may thus be highly diachronous. Its deposition may be complete near to the maximum of glaciation thousands of years before deposition begins in areas of final decay. Nonetheless, it still plays a vital role in defining the stratigraphical level within which a glacial phase may lie. Direct dating of glacial tills has, as yet, proved illusive, in spite of published thermoluminescence (TL)-ages on Polish tills (Rzechowski 1986).

There are contrasts in approach to till stratigraphy in different parts of Europe. In the Netherlands all sediments deposited during a single glacial stage are combined into a single formation. In Denmark (Houmark-Nielsen 1987), Great Britain (Rose 1989) and Poland (e.g. Mojski 1985, Rzechowski 1986) the glacial stages are defined on the basis of individual till units which comprise formations with well-marked upper, lower and lateral boundaries and defined with reference to a type-locality. In Germany, most till units are described with reference to their supposed chronostratigraphical position (Ehlers *et al.* 1984, Ehlers 1990).

Correlations between tills are based on superposition and lithological criteria likely to reflect large-scale integration of sedimentary processes, such as large-scale patterns of mineralogy, granulometry, clast lithology and sedimentary and tectonic fabric (e.g. kineto-stratigraphy in Denmark; Berthelsen 1978). Sedimentary structure alone is often a poor guide, as it may merely reflects local depositional processes.

Vertical lithological differentiation in till beds, even across sharp discontinuities, cannot be used as unequivocal evidence of deglaciation separating two glacial events. The existence of extraglacial (or non-glacial) sedimentation at some point is required.

By tracing the indicator erratics or matrix composition of tills to their source, it has proved possible to show that each glaciation which extended across the Northwest European plain underwent a systematic change in flow direction through the glacial cycle. An early-glacial northerly source progressively gives way to a north-easterly then easterly source, presumably reflecting the progressive migration of the ice-sheet's flow divide in an easterly direction (Ehlers 1983). Most approaches link the percentage of erratic pebbles within the till with the provenance areas in Scandinavia. The method was first developed by Hesemann (1930, 1934) and has been widely used both as an indicator of flow directions and a correlation tool in Germany (Lüttig 1958, Meyer 1983) and the Netherlands (Zandstra 1974, 1987). In the Saalian till cover of the Netherlands for example, several till facies can be distinguished (Zandstra 1987) representing changes in the source areas of the erratics and the ice-flow direction (Rappol 1983, 1987) during one ice advance. Changes in the ice-flow directions have also been reported from fabric measurements in Saalian tills from eastern Germany (Eissmann & Müller 1979; Böse 1990) and Denmark (Sjörring 1983, Houmark-Nielsen 1987).

[b] Glaciofluvial and glaciolacustrine sediments

Subglacial fluvial and lacustrine sediments, as found for example in eskers and drumlins, are volumetrically unimportant in modern glaciers compared to their proglacial equivalents, and there is no reason to assume that this situation was different for former ice-sheets. Both glaciofluvial and glaciolacustrine sediments occur predominantly near the glacier margin, sometimes in ice-contact positions. They show strong spatial and compositional variability, from extensive coarse-grained lithofacies associations to local silt and clay beds. An example of the former are the so-called '*Vorschuttsande und -kiese*', sandur deposits overlain by tills, in northern Germany (Meyer 1983).

In many instances the deposits are associated with temporary ice-dammed lakes which formed during the advance as well as during the deglaciation. Although not amenable to direct dating, the duration of these proglacial sedimentation phases in lakes is regarded short. The features are generally of little value for wide correlation. Most occurrences are therefore left unclassified or are only used in relation to morphostratigraphy to identify glacial limits. Where deglacial ice-margins remain stable for longer periods, large glaciofluvial masses frequently give rise to hummocky, kettled topography or they are pushed into major push moraines during subsequent glacier re-advances. Indeed, many of the largest moraines are for the greater part composed of outwash sediment, sometimes associated with glaciotectonic structures reflecting ice-pushing or collapse of buried ice masses.

As the environment in which fluvioglacial and glaciolacustrine sediments form is so dynamic, they tend to represent relatively short periods of time. However, some distinctive glaciolacustrine sediments are wide-spread, such as the Peelo Formation clays in the Netherlands and their correlatives in Germany, the Lauenburg Clay. They appear to fill in the upper parts of a system of elongated basins, dissected under subglacial conditions by the Elsterian glaciation and are overlain by Holsteinian warm stage deposits. A similar sequence occurs in subglacial basins produced during the later Saalian glaciation in the same area where tills are overlain by, often varve-like, laminated clay and fine sand, followed by Eemian warm stage deposits.

[c] Glaciomarine deposits

Glaciomarine deposits also tend to be deposited in relatively narrow zones (Boulton 1990) and therefore represent short time periods when found in the geological record, although the high sedimentation rates common in glaciomarine environments can produce large thicknesses in short periods. In high latitudes, it is normal to find that, at modern sea-level, tills are overlain by glaciomarine beds, reflecting high local relative sea-levels during glaciation because of the strong lithosphere subsidence beneath and just beyond the ice-sheet (Boulton 1990). Rapid subsequent uplift produces emergence and the glaciomarine units are overlain by beach deposits. They can therefore represent very short time periods and are highly diachronous. The sequence is however a highly distinctive marker for glaciation.

In mid-latitude coastal areas however, there is a marked lack of evidence of such a glaciomarine phase above modern sea-level, with the possible exception in the Irish Sea basin during the last glacial cycle (Eyles and McCabe 1991). This may be a result of glacio-isostatic rebound or reflect low ice-sheet surface slopes, and therefore less ice-loading, at the southern margins of the North European ice-sheets resulting from flow over a deformable bed (Boulton and Jones 1979). Deglacial glaciomarine sequences are common along the mountainous west coast of Norway (Mangerud 1983, 1991). These sequences are of special interest because they show phases of ice-rafting reflecting ice margin fluctuations during the deglaciation (Baumann *et al.* 1995)

Glaciomarine (and glaciolacustrine) deposits are, however, widely found below modern sea-level in the North Sea (Cameron *et al.* 1988). The deposits which fill the Elsterian depressions in the southern part of the North Sea (Swarte Bank Formation) are a marker bed in the offshore stratigraphy. Similar deposits are found in channels originating from the last two glacial cycles. Glaciomarine deposits in the central North Sea overlying the Swarte Bank Formation indicate deposition at distance from the Saalian and Weichselian ice-sheets which entered the North Sea from Fennoscandia and Britain.

[d] Glacial landforms and glaciotectonic features

Glaciation has a fundamental impact on earth surface morphology through erosional[13] and depositional[14] processes, which create a new landscape on which subsequent sedimentary and environmental events occur. The palaeogeography of the Northwest and Central European lowlands indeed has been drastically remodelled as a consequence of repeated glacial activity.

The most striking geomorphological features developed by glacial surface processes are the moraine belts and associated basins delimiting ice-limits (*figure 3.4*). They comprise highly variable pre- and syndepositional units, often incorporating older (deformed) formations while their lower boundaries are surfaces of décollement. They also permit the reconstruction of the areal pattern of ice-sheet development, which would be impractical from till stratigraphy alone. As has been mentioned previously, subdivision of the glaciations of the north European lowland was originally based on the so-called '*Endmoränenstratigraphie*'. According to this morphostratigraphical concept all (push) moraines lying within the subsequent maximum glaciation limits, were assumed to be end-moraines or recession-moraines. Two glaciations were, for example, distinguished within the Saalian Stage: the Drenthe and Warthe Substages. Since no intermediate sediments incorporating evidence for interglacial vegetation has been found, it is assumed that they reflect, together with other end-moraine series, ice-marginal positions during different phases of the Saalian glaciation.

Thus, the end-moraines do not necessarily indicate major climatic change and they are in most cases related to short climatic oscillations at the ice-sheet margin.

3.2.2 Sediments generated in periglacial subaerial environments

With the repeated expansion of ice-sheets and periglacial areas during the Pleistocene the mid-latitudes also experienced cold-climate conditions. The most relevant and typical sediments that are produced subaerially in these cold, unglaciated areas include loess and local slope deposits resulting from mass wasting processes.

Loess is the most wide-spread product of Pleistocene periglacial action. The aeolian deposits have been formed in the unvegetated upland areas and lowland plains beyond the margins of the former ice-sheets and extend in a zone from France into China. They are evidence for cold, dry and windy climate conditions indicating the expansion of desert environments that coincided with the mid-latitude glaciation maxima. This concept of 'glacial aridity' is part of the correlation potential of primary loess units alternated by palaeosols.

Subaerial deposition under prevailing humid periglacial climate conditions comprised various kinds of locally derived slope deposits, one of which may be reworked loess. Distinction between the different types of slope deposits is not always clear, however. Sedimentary products associated with mass wasting and frozen ground constitute common elements in local stratigraphies as well as cryogenic structures. The latter may be post-depositional and will be discussed in *section 3.2.7*.

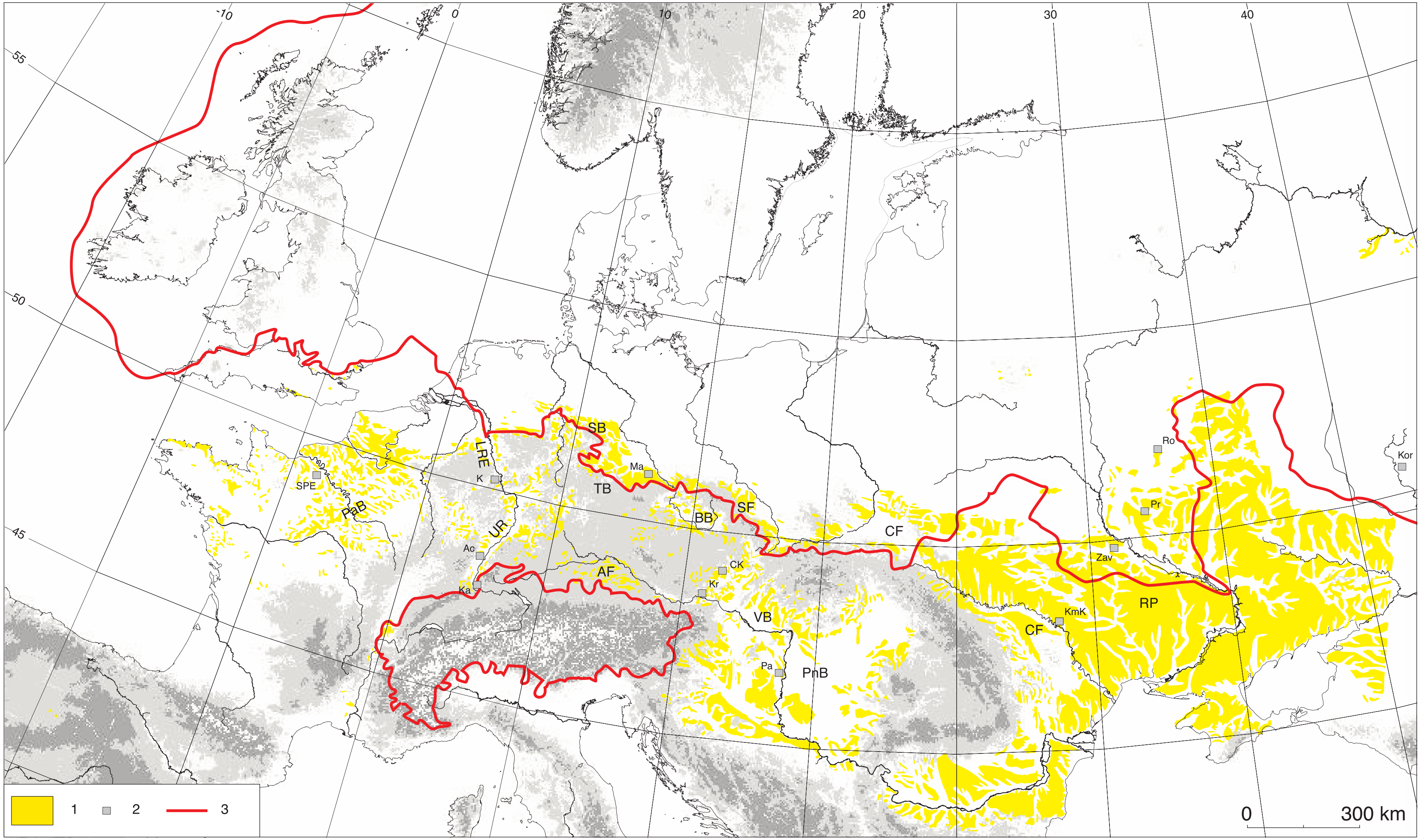


Figure 3.5 Distribution of Pleistocene periglacial subaerial loess sequences in Northwest and Central Europe (from ‘International Quaternary Map of Europe’, UN/BGR 1965-1995). 1. extent of Late Pleistocene loess sequences, 2. some key-stratigraphical localities in Northwest and Central Europe: Ac: Achenheim, CK: Cervený Kopec, K: Kärlich, Kr: Krems, Ma: Mahlis, Pa: Paks, SPE: St. Pierre les Elbeufs, 3. maximum limit of glaciation during the Pleistocene.

[a] Aeolian deposits

Aeolian periglacial deposits are primarily represented by loess and fine to medium-grained (cover) sands. Loess, consisting of wind-blown calcareous silt-sized material, covers extensive mid-latitude areas that were marginal to former Pleistocene ice-sheets (*Fig. 3.5*).

Two types of loess sequences may be distinguished in the aeolian record (Kukla and Çilek 1996): a) plateau (platform) deposits and b) valley slope deposits. Sedimentation and pedogenesis in these two types of deposits proceed in different ways. The platform sequence accumulates entirely from subaerial dust deposition (e.g. China Loess Plateau). Slope deposits are sedimentary fills of depressions usually formed at the lee-side of steep terrace faces cut in bedrock by meandering Pleistocene rivers (e.g. Červený Kopec (*Fig. 2.2*)). Next to primary loess, the latter loess sequences frequently show reworking on a local-scale commonly explained by rainwash and nivation processes as can be recognised by fine wavy laminations, lenses or horizons of sand and fine gravel or interstratified molluscs. Reworked loess deposits are generally referred to as loess derivates or have regional terms like '*brickearth*' (southern England) and '*Schwemmlöß*' (Germany: colluvial loess).

Loess sequences do not record continuous deposition. Series of loess beds are mostly interstratified with soil complexes which reflect gaps caused by non-deposition during warm and humid climate intervals of (forest) vegetation. The soils, humic or leached, can be used broadly to indicate a warm-stage character. However, because soil formation is influenced by a wide variety of independent, local factors (Catt 1988), the potential of buried soils for use as detailed palaeoclimatic markers is limited (see also *section 3.2.7*). Moreover, phases of erosion or non-deposition may result in hiatuses or polycyclic soils (pedocomplexes). Additional palaeoclimatic information from loess is yielded by microfaunal data, e.g. mollusc assemblages, that may indicate contemporaneous temperature and moisture conditions (*section 3.3.2*). Horizons between the primary loess units also may contain mammalian fauna, pollen and artefacts.

The loess stratigraphy of the Central European extraglacial zone is analogous to the till stratigraphy of the glaciated areas, although individual loess units probably represent longer proportions of each glacial phase. The stratigraphical potential of loess sequences increases when more loess/palaeosol cycles are stacked; in vertical superposition as in China and Tadjikistan or in a 'telescopic superposition' like in Central Europe (Kukla and Lozek 1961). Long stratigraphical sequences which appear to include all the principal elements of late Quaternary glacial-interglacial cycles, occur in Slovakia and Austria where they are associated with river terraces (Kukla 1970, 1977), in southern Ukraine (Veklich 1969, Veklich *et al.* 1993) and on the Russian Plain (Velichko 1990). Other less lengthy sequences are found in the Upper and Middle Rhine Valley, e.g. Achenheim (covering the last 3 climatic cycles: Heim *et al.* 1982, Rousseau & Puisségur 1990), Kärlich (Brunnacker *et al.* 1969) and Ariendorf (Brunnacker *et al.* 1975), and also in northern France along the rivers Seine (St. Pierre les Elbeuf: Lautridou 1982) and Somme (Antoine 1991, 1995). Typical loess is, however, found quite infrequent in Northwest Europe; many interruptions resulting from slopewash or some kind of gravitational flow occur.

The loess/palaeosol sequences provide a link between the deep-ocean record and the classical glacial stages on land. Kukla (1970, 1975) correlated the terminations of the marine isotope record with his 'marklines' in the loess successions of Červený Kopec (*Fig. 3.2*). These are boundaries between thick layers of loess, containing gastropods reflecting cold, dry conditions and overlying warm-stage soils[15] and hillwash, indicating abrupt ameliorations of climate. The marklines delimit glacial cycles. Within each glacial cycle, less well developed soil types are distinguished indicating climatic substages. The warm-stage soils often contain molluscs and plant remains indicating formation under typical forest vegetation. When combined with palaeontological, thermoluminescence (TL) and geomagnetic dating, the long-term loess/palaeosol sequence gives a fairly solid (age) match with the oceanic MIS.

[b] Mass wasting products

Most wide-spread in present and former periglacial areas are the subaerial deposits on and at the foot of slopes, filling depressions and stream valleys. They result from the combined effect of gravity movements (mass wasting), soil frost, rainwash and stream activity. Of all categories of mass wasting processes, the most common and effective one was solifluction: the slow downslope movement of water-saturated material (Andersson 1906). Solifluction is favoured in treeless situations and over permafrost, although the latter is not a prerequisite[16]. Solifluction phenomena on low-angle slopes like the '*Head*' deposits in Britain and Ireland or '*Fließerde*' in Germany reflect levelling of the regional morphology characteristic of areas suffering polar climates. The lithologically highly variable sediments generally are heterogeneous, unstratified and poorly sorted diamicton. The sheets and lobes in which they occur may display crude sorting into lenses or pockets of finer and coarser material as a result of differential density flow. The presence of these flow structures, indicating the degree of deformation, is one of the main criteria to distinguish them from the original sediments from which they are derived. Also loess and former soils may be incorporated in solifluction features. The latter which are termed para-autochtonous and give rise to misinterpretations in local stratigraphies.

The stratigraphical value of most solifluction deposits is limited in general, because they consist of reworked local material, including their fossils. They are, however, useful as general indicators of periglacial (cold and humid) conditions in subaerial environments, although direct interpretation is not always possible. In many cases they cover or separate other stratigraphical units or archaeological horizons and protect them from erosion.

3.2.3 Coastal marine and shallow sea sediments

Although sediments deposited in shallow seas under non-glacial conditions tend to be individually more extensive than those on land, they show many of the same problems of discontinuity in time and space. Their great advantage derives from a technique, continuous reflection seismic profiling, which permits their geometry and seismostratigraphical sequence to be established along any arbitrarily defined line, in contrast with terrestrial sequences onshore, which depend upon chance exposures or expensive boreholes.

The non-glacial marine units comprise intertidal and shallow marine sands and clays deposited during high (eustatic) sea-level stands in warm climatic intervals. Marine sequences are often incomplete as the advancing sea-level front is predominantly erosive. In most cases only the basal parts of the sequences have been preserved. Upper boundaries are time-transgressive and difficult to identify. Marine transgressions in the North Sea basin at the beginning of warm stages, when global sea-level is rising as a consequence of ice-sheet melting, have been identified for Cromerian

Figure 3.6 The distribution of basinal and terraced marine deposits in the onshore areas of Europe (from ‘International Quaternary Map of Europe’, UN/BGR 1965-1995). 1. areal extent of Pleistocene marine sequences, 2 maximum extent of the Eemian Sea in Fennoscandia, in the Baltic and adjoining parts of Russia (from Forsström *et al.* 1988), 3. present coastline, 4., 5., 6. important marine terrace localities.

IV, Holsteinian, Eemian and Holocene sequences. Lithostratigraphically these transgressive deposits mark the upper boundaries of the preceding Cromerian C, Elsterian, Saalian and Weichselian glacial stages.

Sediments deposited in marine environments in non-glacial conditions are now well known from the North Sea and the Baltic region from coring and seismic profiling studies. Warm-stage marine sequences are found on land in western and northern Denmark (Tornskov, Skaerumhede: Knudsen 1985, 1987, Lykke-Andersen 1987, Seidenkrantz 1996), northern Germany (Holsteinian type locality: Menke 1968, Dockenhude: Meyer *et al.* 1994), the Netherlands (Eemian type locality at Amersfoort: Zagwijn 1961, 1983 and Amsterdam-Terminal: Van Leeuwen *et al.* 2000), in northern France/Belgium (Holsteinian parastratotype at Herzeele: Sommé *et al.* 1978, Lautridou 1982) and Britain (e.g. Nar Valley: Ventris 1996). Warm-stage marine deposits along the Baltic Sea are known from Eastern Germany (Rostock: Gehl 1961) and Poland (Lower Vistula Sztum and Tychnowy marine series: Makowska 1986, Head *et al.* 2004), as well as from localities in Denmark, Lithuania, Latvia and the Kalingrad district.

Pleistocene marine deposits occur above modern sea-level where they have been uplifted by progressive isostatic uplift or where they represent warm- stage sea-levels higher than at present. In the North Sea area also factors like isostatic rebound (Lambeck 1993), hydrostatic pressure (Mörner 1980) and subsequent glacial thrusting should be taken into account when correlating and reconstructing marine sequences and their palaeogeography. Preserved Eemian and Holsteinian marine units, outcropping along the coastline of the North Sea and the Channel in England, France and Belgium form terraces up to several tens of metres. In contrast there are the marine deposits in the North Sea basin coastal areas and offshore that have been drowned or buried and occur at positions well below present-day sea-level.

3.2.4 Fluvial and deltaic sediments

Part of the history of the large river systems in Northwest and Central Europe is recorded by terrace sediment series, remains of former valley floors, along their valley sides. Terrace formation is the result of both climatic and tectonic changes in time, affecting the graded profile of the river systems. The initial development of terraces is mainly determined by climatic factors. Terrace deposits largely owe their origin to changes in discharge and sediment supply. Their long-term preservation is closely related to the prevailing tectonic regime within the different parts of drainage basins (Veltkamp and Van den Berg 1993).

The key point about terraces is that the sediment sequences and the surface developed upon them are two different things. The term 'terrace' is a morphological feature. The sediment sequences preserved below terrace surfaces are often internally complex, potentially preserving remnants of several cycles of deposition on a range of scales. The surfaces themselves may not be developed on fluvial sediments alone but on subaerial slope and aeolian sediments. And the surface may not be in its original form but may have been remodelled by periglacial and/or soil processes, post-depositionally. The age of any particular terrace surface therefore cannot be automatically assumed in either cross- or down-valley situations. It has to be interpreted from the lithostratigraphical sequence of the underlying sediments.

Many terrace sediment sequences reflect successive phases of aggradation and incision in which the older terraces lie at higher elevations due to progressive isostatic uplift and denudation in their catchments. They therefore have the advantage of showing unequivocal age sequences, although they represent very limited areas. Of particular importance in palaeoclimatic interpretation are sequences for rivers draining areas of slow continuous uplift in the extraglacial zone and which were not influenced by glacial meltwaters like the river Somme in northern France (Antoine 1990).

The response of other rivers to long-term climatic change may be a response to more complex events within the catchment (Baker 1983). Nevertheless, field evidence suggests that the greater part of the coarse-grained terrace sediments in Northwest Europe have been deposited during cold stages (Gibbard 1988). The channels cut in these terrace levels frequently contain distinctive clay and organic beds which contain evidence of warm-stage vegetation and fauna. The units of the long terrace sequence in the midstream regions of the Somme valley (Antoine 1990), for example, include fine-grained, meandering channel deposits in their upper parts.

Thickest fluvial and deltaic sequences occur in subsidence basins, such as in the Upper Rhine Graben and in the North Sea basin. Fluvial sequences here occur in vertical superpositional situations because tectonic downwarping is operating at a sufficiently high rate that the incisional phases are unable to remove pre-existing sequences. Recognition of the geometry and of erosional unconformities, as well as petrographical studies and heavy-mineral analysis here is only possible from cores.

The Middle Pleistocene alluvial plain and terrace sequences in the lower sections of rivers draining northward into the glaciated areas, like the Elbe, Weser and Rhine also reflect responses to downcutting and aggradation cycles as a result of sea-level fluctuations, glaciations and glacio-isostatic effects. They are interbedded or interfinger with marine and glacial sequences and are preserved as depositional units in both morphological terraces and in vertical superposition.

Middle to Late Pleistocene terrace stratigraphies, based on morphological, sediment-petrological, lithological (and palaeontological) criteria, have been developed for the middle and/or upper sections of the Thames (Gibbard 1985, Bridgland 1994, Bridgland and Schreve 2001), Lower Thames (Gibbard 1994, 1995), Somme (Bourdier *et al.* 1974), Maas (Veltkamp & Van den Berg 1993, Van den Berg 1996), Lower Rhine (Brunnacker *et al.* 1978; Klostermann 1992), Middle Rhine (Bibus 1980), Weser (Lüttig 1974), Elbe/Saale (Eissmann 1975), Elbe/Ilm (Mania 1989), Elbe/Vltava (Tyracek 2001) and the Danube/Srvatka (Kukla 1975, Gábris and Nádor 2006). Loess sequences and palaeosols covering the terrace surfaces provide supplementary stratigraphical means to elaborate the non-glacial succession in Central Europe.

3.2.5 Lacustrine sediments deposited in lakes, peat bogs and abandoned meander channels

Lake sediments form in small-scale basin settings which owe their origin to a variety of geological and geomorphological aspects. Their formation may be due to:

- Tectonics such as the lakes of intramontane and non-marine subsidence basins (e.g. Tenaghi Philippon and Ioannina),
- Various kinds of glacial processes like the lakes in glacial outwash or till,
- Periglacial phenomena such as remnants of pingo's and thermokarst,
- Volcanic activity (e.g. the crater lakes in the Central Massif),
- Subsidence and collapse structures resulting from salt dissolution or karst,

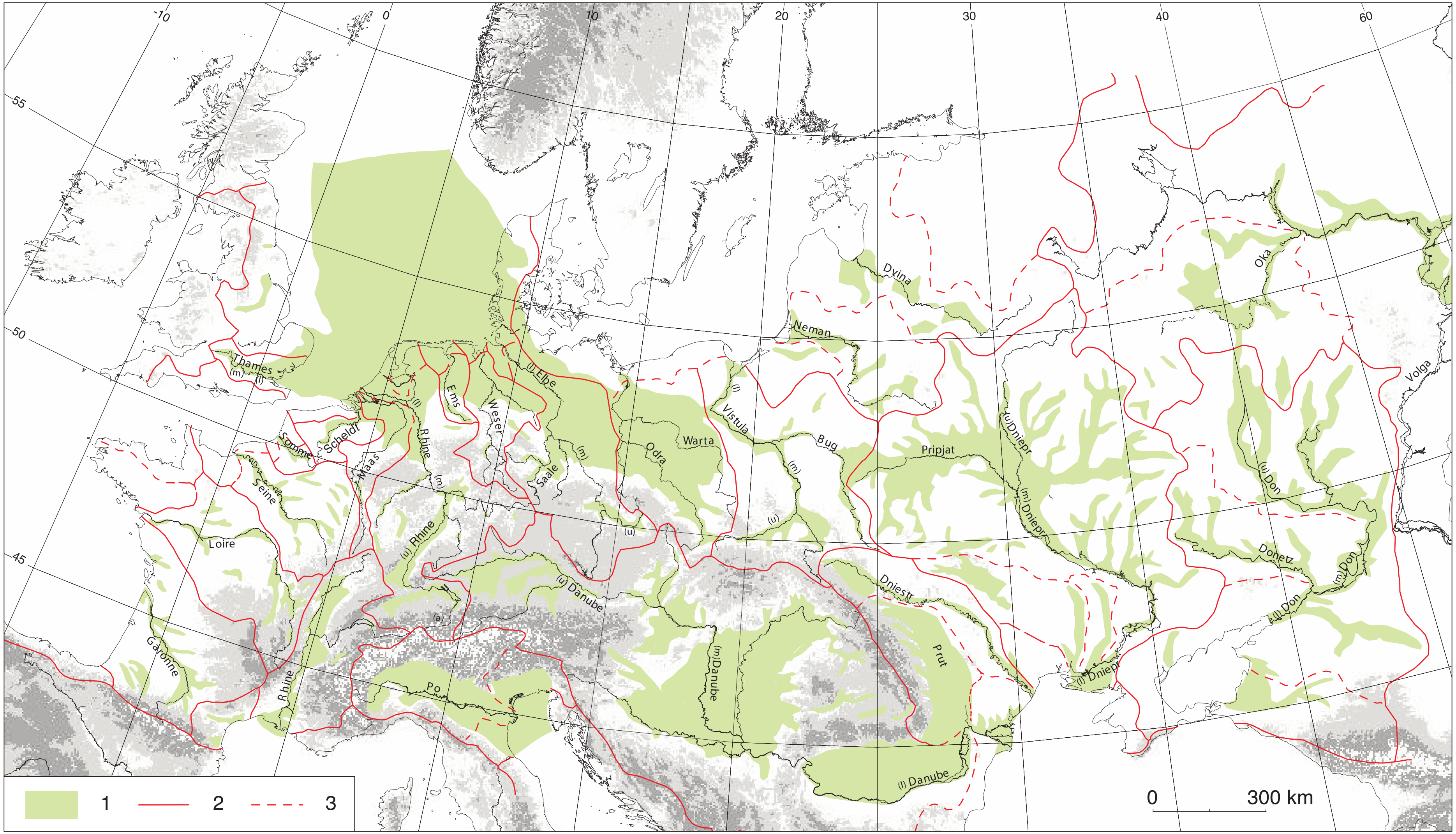


Figure 3.7 Distribution of fluvial sediments and drainage basins in Northwest and Central Europe (from 'International Quaternary Map of Europe', UN/BGR 1965-1995). 1. extent of fluvial and deltaic sequences, 2. main water divide, 3. secondary water divide.

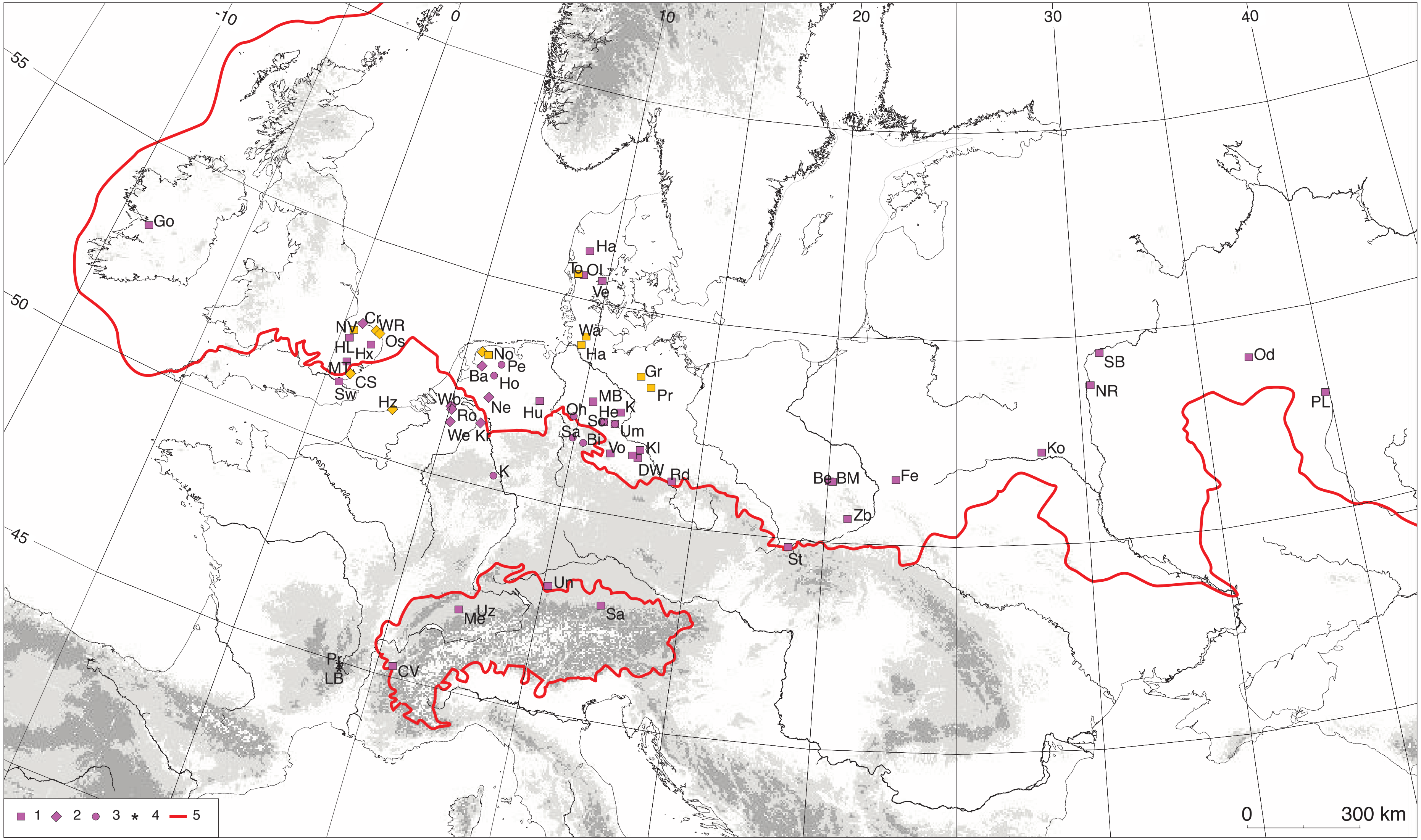


Figure 3.8 Distribution of lake and mire sequences in Northwest and Central Europe (from ‘International Quaternary Map of Europe’, UN/BGR 1965-1995). 1. glacial lake sequences, 2. fluvial lake sequences, 3. solution lake sequences, 4. maar lake sequences (LB: Lac du Bouchet, Pr: Praclaux), 5. maximum limit of glaciation during the Pleistocene.

Saalian Stage: Ba: Bantega, Bi: Bilshausen, Ho: Hoogeveen, Ka: Kärlich-Seeufer, Sc: Schöningen, Ve: Vejlby, Zb: Zbojno; Holsteinian Stage: CS: Clacton-on-Sea, Gr: Granzin, He: Hetendorf, HL: High Lodge, Hx: Hoxne, Hz: Herzeele, Kl: Klieken, Kr: Krefeld, MB: Munster-Breloh, MT: Marks Tey, NV: Nar Valley, Ne: Neede, Pr: Pritzwalk, Sw: Swanscombe, To: Tornskov, Wa: Wacken; ‘Cromerian Complex’ Stage: Cr: Cromer, Fe: Ferdinandov, Ha: Harreskov, Hu: Hunteburg, Ko: Kosteschi, NR: Nidschinski Row, No: Noordbergum, Ol: Ølgod, Os: Ostend, Od: Odintsovo, PL; Poljno Lapino, Ro: Rosmalen, Sk: Shklov, Vo: Voigtstedt, We: Westerhoven, WR: West Runton.

- Abandonment of meander channels in fluvial depositional environments.

Small shallow lake depressions in unlithified sediments are readily infilled, but even large depressions with large catchments can receive a sufficiently large clastic sediment input to have only a short life before being infilled (Mangerud 1983). Larger, deeper lakes are generally subject to strong circulation which may generate internal patterns of erosion and deposition which vary in time and space and which are subject to highly erosive turbidity flows. Thus, in such lakes, even where cores can penetrate deep enough to sample long time spans, they do not always sample continuous sequences and may only reflect major events. Selection of lake sites and the location of boreholes within a lake sequence is very important to obtain the relevant information.

Sequences particularly from lakes with a closed system and with a small catchment show basically continuous, low energy deposition. Although in the case of glacial lakes they usually do not exist for a long period of time, their preservation potential is high, being sandwiched between (or overlying) glacial deposits. Such lake sediments are important sources of high resolution data on palaeoenvironmental conditions, be it local to regional.

[a] Lake and mire sequences in formerly glaciated and periglacial areas

In the glaciated zone, the remodelling of the landscape during glacial cycles tends to ensure that no lake basin will have a continuous record of change longer than the last glacial cycle in the area. Small lakes within the glaciated zone may accumulate distinctive organic sequences with a good correlation potential before being overridden by subsequent ice or filled in by periglacial sediment. For instance, warm-stage pollen sequences attributed to the Eemian Stage, were overrun by the ice-sheet of the last glacial cycle, and correlate well with lake sequences which lie beyond the last glacial maximum but post-date earlier glaciations (*cf.* Jessen & Milthers, 1928). Some of these lakes and mires, are particularly valuable in that the initiation of sedimentation within them cannot pre-date deglaciation. They are the ideal sequences to bridge the time between two subsequent glaciations. If organic sedimentation starts early in their life, they can be a valuable guide to date for example the last deglaciation, for which ^{14}C dating is available (Mangerud 1991), or they can indicate similar 'Late Glacial/Dryas' fluctuations during earlier deglaciations, for example in the sequence of Neumark-Nord in eastern Germany.

Some well established local Middle and Late Pleistocene interglacial stratotypes and their correlatives include, from youngest to oldest:

- The Eemian lake sequences at Amersfoort (Zagwijn 1961) in the Netherlands, Hollerup in Denmark (Andersen 1965), Bobbitshole in Great Britain (West 1957), Grande Pile in France (Woillard 1979), Neumark-Nord, Gröbern and Grabschutz in Germany (Mania 1990, Litt 1994) and others,
- The Holsteinian lacustrine sequences at Pritzwalk and Münster-Breloh (Germany: Erd 1973 respectively Müller 1974), Hoxne and Marks Tey (England: Turner and West 1968, Turner 1970), and Tornskov (Denmark: Andersen 1965),
- The Cromerian lake sequences are less well established due to uncertainties in stratigraphical position, although pre-Elsterian in the glaciated areas, and similarities in pollen assemblages. In the Netherlands, Zagwijn (1975, 1996) identified four warm stages are from organic beds in fluvial deposits (I-Waardenburg, II-Westerhoven, III-Rosmalen, IV-Noordbergum; *Fig. 3.1*). Further evidence comes from the former lake sequences at Bilshausen (Germany: Müller 1965, revised in Bittmann and Müller 1996 and in *section 5.2.3*), Harreskov (Denmark: Andersen 1965) and Ferdinandov (Poland: Janzcyk-Kopikova 1975).

[b] Lake sequences from the extraglacial zone

Beyond the limit of the last glaciation, surprisingly few lakes containing a sedimentary record longer than the last glaciation have been found in Europe. The challenge is to correlate these mid- and south-European sedimentary records, extending much further back in time, with those of the former glacial lakes.

Lakes which have formed in small tectonically-controlled basins like Tenaghi Philippon and Ioannina (Greece) and in the craters of small Cenozoic volcanoes in Europe (primarily in France, Italy and Germany), the so-called maar lakes, are ideal sites for long sedimentary sequences spanning several interglacial-glacial cycles. They have very small catchments so that relatively little minerogenic material is introduced to them. However, they are ideal pollen traps. Due to the relatively low sedimentation rates, relatively short cores might represent a long period of time, whilst limited bioturbation and the dominant organic input ensures a rich source of palaeoenvironmental and palaeoclimatic information. The lake sites in eastern France at La Grande Pile and Les Echets currently have pollen sequences which extend back to about 140 ka (Guiot *et al.* 1989, 1992), although the base of the sedimentary sequence has not yet been reached. They have the potential to go back much further in time as in the maar lake sequences of the Velay region in the Central Massif, where at Lac du Bouchet (Reille and De Beaulieu 1995, Tzedakis *et al.* 1997, Reille *et al.* 2000) a lake sequence down to the base of the supposedly Holsteinian corresponding Praclaux warm Stage could be cored (*Fig. 3.9*).

3.2.6 Other sediments from local-scale subenvironments

Some other characteristic sediments in the terrestrial record, although usually local in their occurrence, will be briefly mentioned here: volcanic ash layers, secondary carbonates (travertine, spelaeothems) and cave deposits. They often comprise marker beds which may contain bio- and chronostratigraphical information of decisive stratigraphical interest.

[a] Volcanic sediments

Quaternary volcanic fields are known from several regions in Europe of which those in the Eifel region and the Central Massif have provided Middle Pleistocene chronostratigraphical units dated by tephrochronology. Of interregional stratigraphical importance is the set of tephra beds which enables dating of the Middle and Late Pleistocene loess/palaeosol and terrace sequence in the Middle Rhine Neuwied basin (e.g. Van den Bogaard and Schminke 1990). Further downstream, in the Lower Rhine Embayment and in the Netherlands, as part of the glaciated southern North Sea basin, their incorporated and fluvially transported heavy minerals are used as lithostratigraphical markers and as indirect dating and correlation tools. Unfortunately, dating and chrono-correlation are not unequivocal in these regions which will be discussed in more detail in *chapter 5*.

[b] Secondary carbonates

Carbonate sediments are formed by cementation and precipitation from springs, lakes or rivers in limestone areas. They may be of thermal or cold origin, locations of which are reviewed in Pentecost (1995). Travertine forms as a dense cryptocrystalline calcite occurring as subhorizontal beds in river valleys. Tufas form through precipitation on growing plants and commonly are soft and porous. Their stratigraphical value lies in the fact that they indicate relatively warm climate conditions and that their incorporated fossil remains provide often detailed local palaeoenvironmental information (e.g. Bilzingleben in eastern Germany: Mania 1973, 1993, also Hitchin in England: Kerney 1959).

Spelaeothems are subsurface carbonate precipitates found in cracks and caves. Although stratigraphically unimportant, their chemical analysis may yield local records of oxygen isotope fluctuations (*section 3.4.3*) which may be helpful in local palaeoclimate reconstructions.

[c] Cave and rock shelter deposits

Caves are the result of various processes of groundwater solution and part of karst geomorphology in limestone areas or may occur as rock shelters or abris in other bedrock. Cave deposits are highly variable and of local origin although extraneous sediments may have been brought in by water, wind (e.g. loess) and gravity action.

Caves and rock shelters are of special interest for palaeontologists and archaeologists since animals and man sought shelter in caves. Many important Palaeolithic sites are located in these environments where calcareous preservation conditions are generally good. Their chronostratigraphical position, however, generally remains indistinct because of the very low correlation potential.

3.2.7 Syn- and post-depositional structural features

Once laid down, sediments are prone to all kinds of geological and chemical processes that may alter their original properties; by collapse, slope processes/mass wasting, weathering and soil formation, compaction, diagenesis and glaciotectonics. Two features will be briefly discussed because they are indicative for climatic change or specific climatic conditions during non-depositional time intervals:

[a] Cryogenic structures

Many characteristic cold climate features may be found in any area with regular frost activity and are not indicative of any thermal limit. Cryogenic structures produced by intense frost activity are commonly found in aeolian periglacial and other cold climate sediments.

Involutions and features indicating permafrost occur at particular horizons and hence indicate contemporaneous climate. Their appearance and distribution are a valuable complementary source for palaeoclimatic interpretation (Strunk 1983; Karte 1987). Nevertheless, one should be careful with temporal interpretations because they may be post-sedimentary phenomena.

Sedimentological and morphological characteristics diagnostic of the occurrence of continuous permafrost[17] are:

- Ice- and sand-wedge casts and polygons, the most strict indicators of permafrost,
- Pingo-remnants.

Both are superficial permafrost phenomena and do not indicate to its thickness. Reconstruction of Pleistocene permafrost is so far focussed on the Weichselian cold Stage and have been undertaken in the Netherlands and Belgium (Vandenberghe 1985, 1992; Haesaerts 1984), and eastern Germany (Eissmann 1981). Evidence of permafrost of Saalian age has, so far, been demonstrated by Eissmann (1981) in eastern Germany. Based on the cryogenic deformation of lignite layers in non-glaciated areas, he indicated a minimum permafrost depth of 50 metres, and suggested a maximum of more than 100 metres.

[b] Pedogenic structures: soil complexes

Soils can be sediments in situations where sediment is pedologically modified as it is laid down - e.g. in Chinese loess sequences. But generally they are not where sedimentation does not occur during soil formation. Soil formation is polygenetic and primarily a function of climate and topography and secondarily of substrate, maturity (time) and organic activity (Catt 1988, 1995). Most soils are soil complexes and are composed of different soil types. One should therefore be cautious with soil-stratigraphy because of the lack of knowledge of the complex relationships between soil properties and climatic factors (Haesaerts and Mestdagh 2000). Moreover, the ability to estimate the lengths of soil-forming intervals is restricted. Nevertheless, buried and surface soils, in particular in aeolian sequences, hold great potential for Quaternary palaeoclimatic interpretation since they indicate warm vegetated climatic conditions. As discussed in *section 3.2.2*, palaeosols are used as marker events within the long extraglacial loess records of Eurasia, indicating periods of non-deposition during warm palaeoclimatic stages. Soil complexes found in the Central European type regions are of two main groups (Kukla 1977):

- Biogenic steppe soils (chernozems), showing accumulation of organic matter but little chemical change in mineral matrix, and
- Brown leached soils with evidence of in-situ redeposition of carbonate, iron or manganese as well as clay plasma, but reworked by pedofauna to only a minor degree.

Parabraunerde-type soils with a Bt-horizon are the product of deciduous forests. They are the most common found warm-stage palaeosols in the extraglacial areas of Northwest and Central Europe and have a high stratigraphical value.

3.3 Biostratigraphical datasets in terrestrial sequences

Preserved fossil remains in different Pleistocene sedimentary environments provide relative, local and regional chronologies as well as information for palaeoenvironmental and -climatic interpretation. The most useful fossil groups are those that can be identified readily on a species level and those that have undergone significant evolutionary change (Bridgland and Maddy 2002). Subdivisions based on evolutionary change in flora and fauna are restricted, however, for such a short time period such as the Middle Pleistocene. In some cases it is possible to indicate a general age or constrain a time-range on the basis of extinction or of migration patterns of indicator species.

Assemblage biozones have proven to be a powerful stratigraphical tool in the recognition of Pleistocene palaeoclimatic stages in Europe (*section 3.1*). They are useful event markers when applied on the basis that the ecological response of organisms to a complex sequence of environmental and climatic changes is unlikely to generate identical assemblages at different periods. This assumption is most likely to be true for the relatively short warm stages with a rich and varied biota, but not for the long cold periods in which biotic production and biological diversity is reduced[18]. In particular, it is the rich warm stage floras and microfaunas which are assumed to be compositionally unique and which have potential to form the essential correlation horizons for the Pleistocene stratigra-

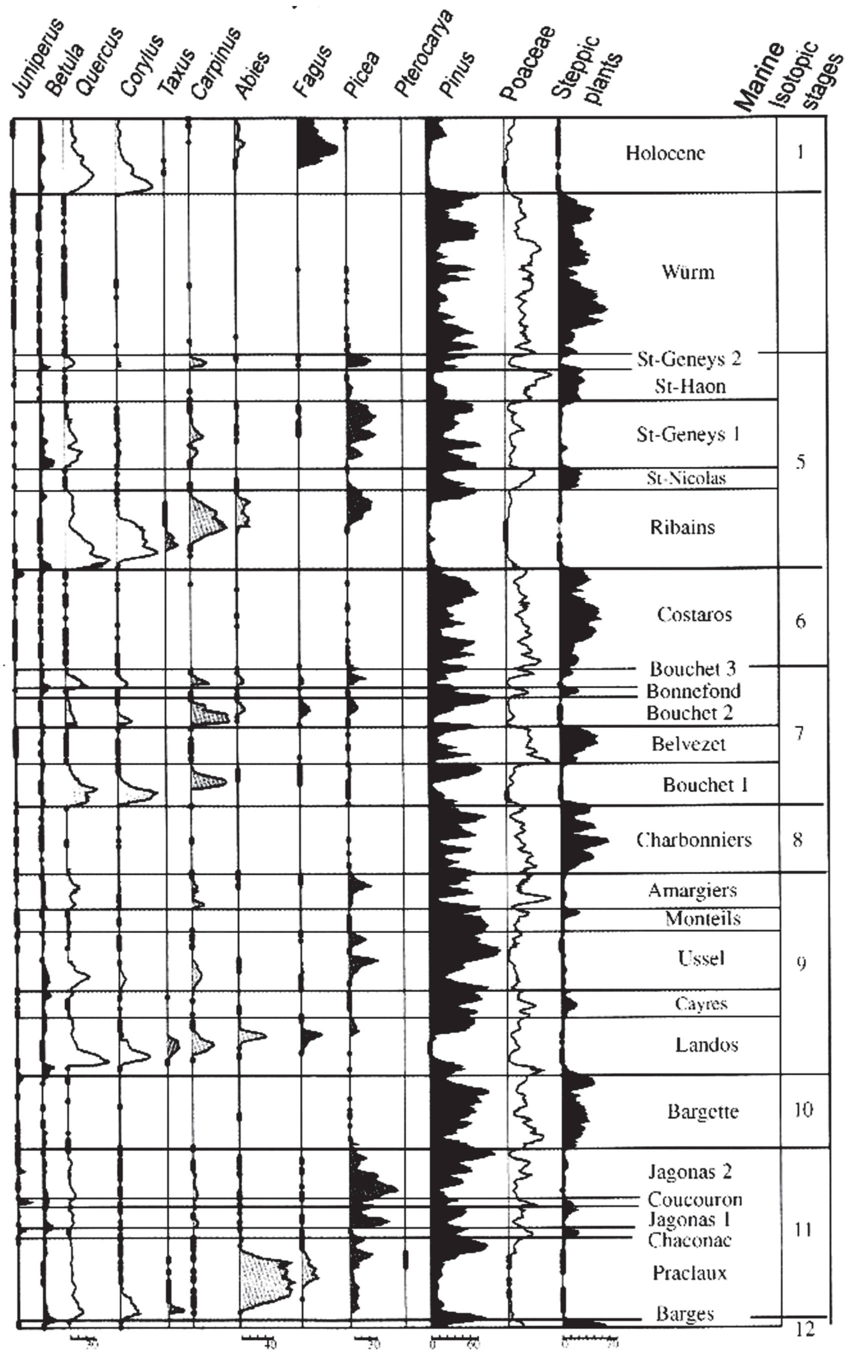


Figure 3.9 Late Middle Pleistocene pollen stages and interpreted stratigraphical relations of the maar lake sequences in the Central Massif (Reille *et al.* 2000). A tephra within the Amargiers pollen assemblage zone is dated at 287 ka (Reille and De Beaulieu 1995).

phy. One should, however, always consider its relation with the depositional environment, because of effects of reworking and inwash. Sedimentary environments and main type localities in which fossil remains are preserved have been reviewed in *section 3.2*.

A brief outline of the use and limitations of various fossil groups which play a role in distinguishing between regional stratigraphical sequences and events is given below.

3.3.1 Palaeobotanical evidence

The Northwest European continental Middle Pleistocene stage succession is largely based on a sequence of palynologically distinctive stratotypes reflecting warm-temperate climate conditions. They are generally from lacustrine environments from different origin (summarised in *section 3.2.5*) intercalating the glacial sequences. Pollen and spore assemblages are also recovered from soils and even from marine environments. Many vegetational histories only record parts of the time represented in any individual warm climatic stage. They may in later phases be influenced more and more by edaphic and other local factors which hamper correlation. Regional variations and correlation over long distances or with fragmentary data should be regarded cautiously.

Zonation schemes of vegetational development (*cf.* Turner and West 1968) enables subdivision within and between warm stage forest pollen spectra from Northwest Europe. A full climatic cycle comprises four substages of forest vegetation assemblages which, for example, have been applied to subdivide the pollen diagram for the British Hoxnian temperate Stage from Marks Tey (*Fig 3.10*):

- Substage I (Pre-temperate phase): boreal vegetation lacking

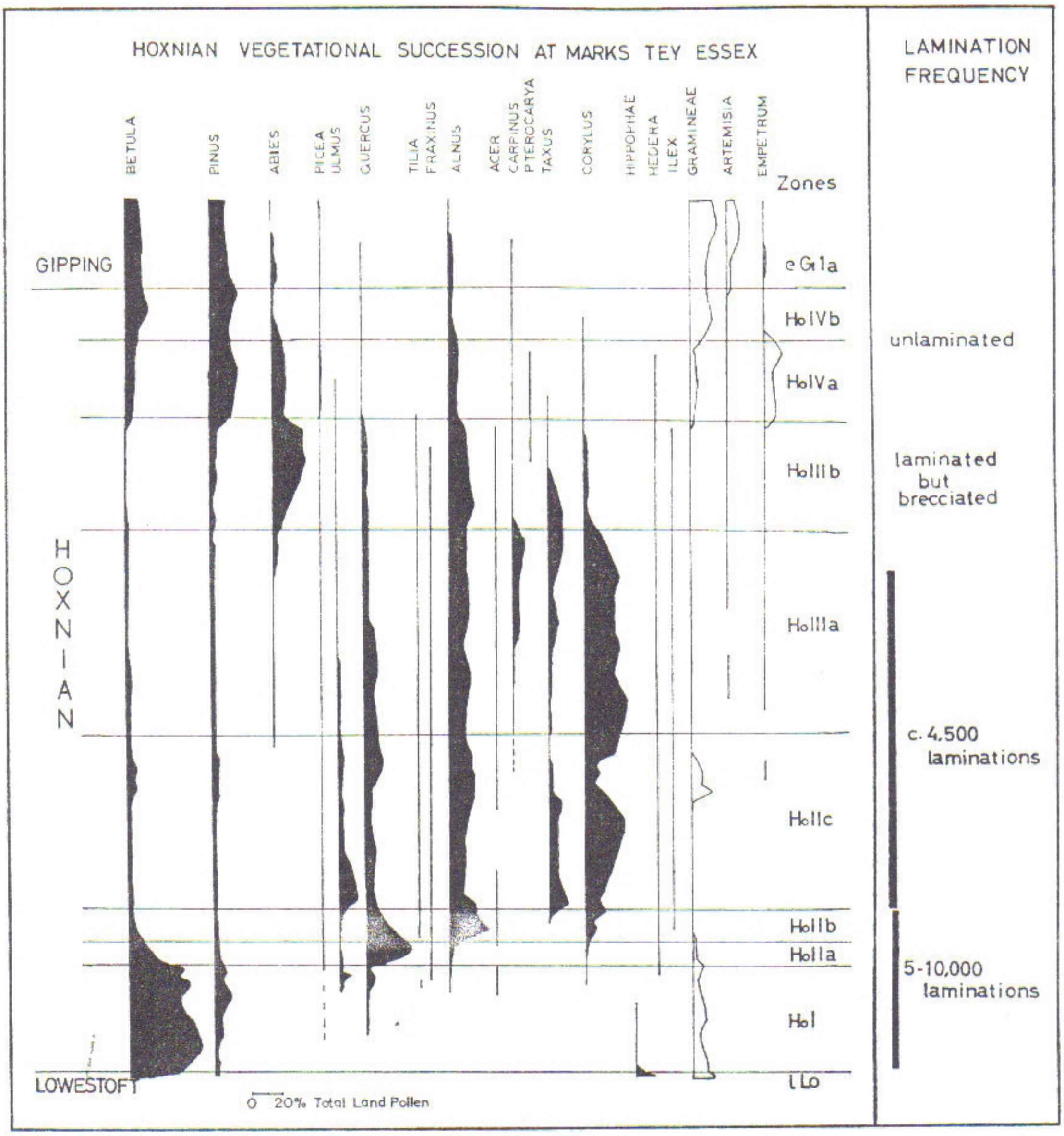


Figure 3.10 (Composite) pollen record typical for the vegetational succession of the Hoxnian temperate stage from Marks Tey (after Turner 1970).

temperate elements, but with evidence of birch and pine forest,

- Substage II (Early temperate phase): phase of deciduous forest and broadleaved trees with development of mixed oak (QM) forest type assemblages,
- Substage III (Late temperate phase): phase of deciduous forest and broadleaved trees with presence of late expanding trees like *Carpinus* and *Abies* at the expense of the mixed oak forest,
- Substage IV (Post temperate phase): in which there is a limited representation of thermophilous, broadleaved species and boreal forest is recurring.

Despite some limitations (De Jong 1988) such pollen assemblage zones provide distinctive markers of individual climatic phases and may indicate in which part of the climatic cycle a sediment was laid down. Also the behaviour of certain tree species in relation to zonal climate aspects can be studied. In general, the limited boreal-type palynofloras and the 'open tundra' vegetation assemblages (with shrubs and herbs) of stadials and interstadials inhibits their use as indicators of specific stages.

Pollen assemblages may contain specific indicators for distinguishing between temperate-climate periods. Examples of indicator species in Middle Pleistocene warm Stage pollen assemblages are:

- *Eucommia*, *Pterocarya* and *Celtis*, indicating the decrease in Tertiary assemblages and relict pollen in Middle Pleistocene deposits. *Pterocarya* for example occurs in pollen diagrams up to and including the Holsteinian warm Stage,
- The water fern *Azolla filiculoides*, indicative of a pre-Eemian age,
- *Abies*, indicative of oceanic influence in the Northwest European lowlands accompanied by high sea-level stands such as occurred during the Holsteinian and Eemian warm Stages (Zagwijn 1989, 1992).

Of major interest is how the independent, scattered and fragmentary pollen evidence from the glaciated Northwest European areas correlate with the long continuous pollen records of Tenaghi Philippon in Greece (Mommersteeg *et al.* 1995) and Lac du Bouchet/Praclaux in southern France (Reille and De Beaulieu 1995, *Fig. 3.9*). Both comprise local proxy palaeoclimate records which are a link to the marine isotope stratigraphy. Comparison, by trend matching, is now well established for the late Middle and Late Pleistocene (Tzedakis *et al.* 1997, Tzedakis *et al.* 2001). Additionally, pollen from marine cores off-Portugal have been directly correlated for MIS 5 (Sánchez-Goñi *et al.* 1999) and for MIS 11 (Desprat *et al.* 2005). On the basis of the last appearance datum (LAD) of *Pterocarya* pollen in the Praclaux warm Stage, Reille and De Beaulieu (1995) and De Beaulieu *et al.* (2001) suggest that this stage probably corresponds to the Holsteinian of northern Europe. This implies correlation with MIS 11 and the existence of two additional warm climate events within the late Middle Pleistocene Saalian Stage, preceding the Saalian glaciation sensu stricto.

3.3.2 Palaeozoological evidence

Faunal remains in the terrestrial sediments play a less important role in Middle Pleistocene biostratigraphy than does pollen. Distinctive fossil assemblages suitable for biozonation and chronostratigraphical subdivision are rare due to the fragmentary evidence, the often low frequency and the lack of distinguishing criteria. Moreover, their occurrence is often restricted to specific sedimentary environments, which makes correlations difficult. Biostratigraphical correlations on the stage of evolutionary change, extinction and migration of species, the latter factors are related to climatic change, are only possible for vertebrate and molluscan faunas and have given some subdivision in the Early and Middle Pleistocene. Their value in reconstructing climatic change in most cases is limited to the assignment to warm or cold stages. Nevertheless, many sites in Northwest Europe have yielded rich faunal remains, some of which are used as regional stratigraphical markers (summarised in *section 4.4.2* and *Fig. 4.9*) reflecting environmental conditions.

[a] Vertebrates

The preservation of mammalian bones and teeth in sedimentary environments such as non-acidic lakes margins and mires, spring surroundings, loess regions and floodplains, have allowed reconstructions of fossil vertebrate assemblages in a number of local stratigraphies. A review of presence/absence data of mammalian assemblages in Middle and Late Pleistocene warm stage fluvial terrace sequences from Britain and the German uplands is compiled by Schreve and Bridgland (2002). From their correlations they suggest there is evidence for three warm events within the late Middle Pleistocene post-dating the Elsterian/Anglian glacial sequences.

Biozonation of fossil micromammal assemblages for the Middle and Late Pleistocene in Northwest Europe (Van Kolfschoten 1990, Horacek 1990) reveal temporal change in molar composition of some species. Of particular importance for the early Middle Pleistocene stratigraphy is the boundary of the rodent species *Mimomys savini* and *Arvicola terrestris cantiana*. A further marker forms the gradual change in the thickness of the enamel in the *Arvicola* lineage[19] that took place between the Elsterian and Saalian glaciations (Van Kolfschoten 1990).

[b] Molluscs

Although they supply the raw material for amino acid racemization, the Mollusca are of limited value for dating purposes. They occur in all kinds of environments, land, freshwater and marine, and are therefore powerful palaeoenvironmental and palaeoclimatic indicators.

Terrestrial gastropods in loess sequences in Central Europe (Kukla 1977) and at Achenheim, France (Rousseau & Puisségur 1990) have provided valuable information on loess and soil environments. Based on the work of Lozek (1965) several shell faunal assemblages can be distinguished, ordered in decreasing warmth requirements:

- *Banatica* fauna, indicator species *Helicigona banatica*, a warmth-loving assemblage, found in spring travertine among others,
- *Pomatia* fauna, indicator species *Helix pomatia*,
- *Tridens* fauna, indicator species *Chondrula tridens,*
- *Striata* fauna, indicator species *Helicopsis striata*,
- *Pupilla* fauna, with *Pupilla muscorum* and other *Pupilla* species, as well as *Succinea oblonga*, as indicator representatives,
- *Columella* fauna, with *Columella columella* as indicator species and a biomarker for extreme cold climates.

Freshwater molluscan fauna of river and lake deposits provide valuable biostratigraphical constraints:

- The occurrence of *Viviparus diluvianus* (= *Paludina diluviana*), characteristic of the Lower Elbe fluvial sequence, is attributed to the Holsteinian warm Stage,
- *Corbicula fluminalis,* another warmth-demanding species, is appearing in several warm-stage fluvial sequences assigned to the Holsteinian Stage and following warm Saalian Stage events, but is absent from Eemian-age deposits (Meijer and Preece 2000). Just as *Viviparus diluvianus*, the presence of *Corbicula fluminalis* is a marker in the fluvial terrace deposits in the uplands of Central Germany (the 'Mittelterrassen') intermediate of the Elsterian and Saalian glaciations.

The use of marine molluscan fauna assemblages is limited because of the lack of distinguishing criteria (Meijer and Preece 1995).

3.4 Chronostratigraphical control on terrestrial Middle Pleistocene sequences

3.4.1 Relative age markers

The age determination of distinctive lithostratigraphical units and biostratigraphical assemblages is based on relative age criteria and often the only chronological method applicable. With the exception of the last 40-50 ka, for which dendrochronology and radiocarbon dating provide reliable timing, older chronostratigraphical land-based subdivisions are mainly based on palynological criteria and superposition. Marine subdivisions, by contrast, are based on (micro-)palaeontological criteria. Layers of volcanic ash of known age and provenance are used as lithostratigraphical markers in the Late and Middle Pleistocene sequence of the Rhine valley. Interglacial marine and fluvial stratigraphical units, containing molluscan fossils from Northwest Europe, have been correlated by aminostratigraphy (Bowen and Sykes 1988). Nevertheless, this chemical method of amino-acid racemisation of molluscan shells is still of limited use for regional correlations of late Middle and Late Pleistocene transgressions. Recent developments have enhanced the reliability of the method (Sykes *et al.* 1995) and has given better results for several fluvial and estuarine sequences (Meijer and Preece 2000, Bridgland and Maddy 2002).

The duration of individual lithostratigraphical units can be determined by the counting of incremental accumulations of laminated sediments found in lakes. Of particular importance are the varve chronologies from proglacial rhythmites in Sweden (de Geer 1912) and from organic algal blooms at Marks Tey in England

(Turner 1970). The latter showed a duration of the Hoxnian temperate Stage in the order of 15-20 ka.

3.4.2 Palaeomagnetic evidence

Palaeomagnetic investigations of Pleistocene sediments provides a general, low resolution timescale requiring long fine-grained sedimentary sequences spanning hundreds of thousands of years. Of particular importance is the position of the Matuyama/Brunhes Chron boundary, the last global geomagnetic reversal, which is taken as the base of the Middle Pleistocene. It is dated at *c.* 780 ka which leaves a considerable gap with the aforementioned dating limits. Some brief excursions are noted within the Brunhes normal Chron. Langereis *et al.* (1997) in their review on short reversal excursions in the Brunhes Chron mention four significant events within the Middle Pleistocene: Calabrian Ridge (CR)0 dated at around 260 ka, CR1 dated at around 320 ka, CR2 dated at around 515 ka and CR3 dated at about 570-575 ka.

Conversely, magnetostratigraphy, in combination with magnetic susceptibility and related techniques, has yielded high-resolution records from long Chinese and Eurasian loess sequences during the last decade which show close similarity with the marine isotope record (Derbyshire (ed.) 1995).

3.4.3 Geochronometric dating

In addition to the relative age methods, whereby a sequential order to the deposits is established, different geochronometric methods such as thermoluminescence (TL, OSL, IRSL and GLSL[20]), Uranium (U)-series, Uranium/Thorium (U/Th)-dating, Electron Spin Resonance (ESR), Potassium/Argon (K/Ar)-, Argon/Argon (Ar/Ar)- and Fluorchloride/Potassium (FCl/P)-dating, are applicable as time-stratigraphical criteria (Geyh and Schleicher 1990). Although essential for the Pleistocene chronology, reliable absolute age estimations for the European continent, however, are scarce up till now. Accuracy of the dating techniques decreases with time. The chronological framework for the Holocene and Late Weichselian time has come from radiocarbon dating. The age determination beyond its limit of 40-50 ka remains troublesome because the techniques are limited, either as a consequence of their time-range or of their sensitivity to particular materials. The maximum dating limit of most of these techniques appears to be 300-400 ka or less.

The dating techniques which are used to calibrate both Middle and Late Pleistocene stratigraphies in Northwest Europe are:

[a] Luminescence dating

The luminescence methods are applicable to grains of quartz and feldspar in silty Pleistocene sediments, e.g. loess. Dates from loesses are obtained from the Rhine Valley area, northern France and Poland. Most determinations are from Weichselian loesses, and give meaningful results. Reliable dates over about 125 ka (pre-Eemian), however, have not yet been obtained, because TL age differentation of Saalian loesses is still not possible (Frechen 1991, 1993). Older (minimum) TL dates, however, are known from burnt flint at Maastricht/Belvédère in the Netherlands (270 ± 11 ka; Huxtable & Aitken 1985) and aeolian sediments and tills from Poland (Mojski 1985; Rechowski 1986). The latter TL determinations, which apparently extend into the Early Pleistocene, are questionable due to the various analysis techniques which are used. Luminescence methods such as IRSL and GLSL are used for dating of fluvial sequences.

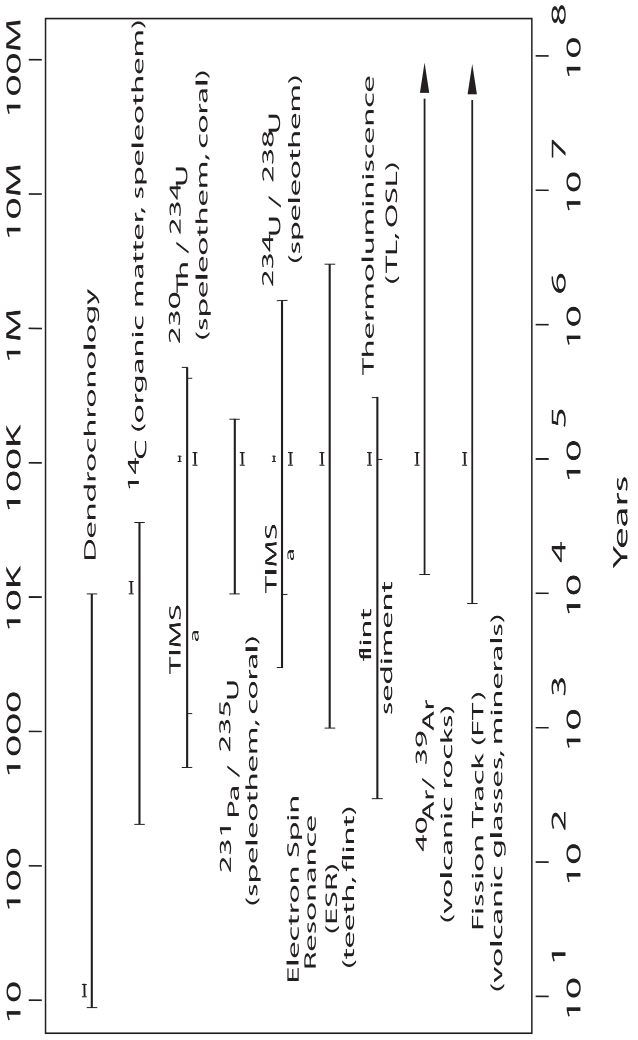


Figure 3.11 Quaternary dating methods and their time-ranges (after Stein and Linse 1993).

[b] Uranium Series dating

U-series and ESR dating can be a suitable method as far back as the Middle Pleistocene, although the dating limit appears to be about 300-400 ka. The method is most applicable to precipitated carbonate deposits and concretions. Fairly accurate dates can be obtained from cave deposits (speleothems). Presence and growth of these deposits occur during non-glacial climatic conditions, which can be derived from their oxygen isotope content. Dates are available from NW England (Gascoyne *et al.* 1983), suggesting a warm episode between 250 and 230 ka, and from Norway (Lauritzen 1991). Travertine from the Bilzingsleben terrace II has been dated by U/Th at about 320-350 ka, ESR dates range from 280-415 ka (Schwarz *et al.* 1988 in Mania 1993). Travertine from the deposits of the terraces III and IV at Verteszöllös (Hungary) have been U/Th-dated at respectively 360 ka and 200 ka (Hennig *et al.* 1983). U-series of the authigenic carbonate content in Hoxnian warm Stage deposits at Marks Tey revealed minimum dates around 400 ka (Rowe *et al.* 1999).

Moreover, estimates of the age of fossils from warm-stage marine and lacustrine deposits have been determined by U/Th- and ESR dating. Molluscan shells in Holsteinian marine deposits have been determined from Herzeele in northern France (marine unit III: minimum age 326 ka) and from Wacken in Schleswig-Holstein. Based on U-Th dates, Sarnthein *et al.* (1986) assumes that the Wacken marine deposits are older than 350-370 ka, whereas Linke *et al.* (1985) report ESR-data from the same Holsteinian marine deposits at respectively 195 ± 25, 223 ± 25 and 218 ± 25 ka.

Dating of Late Pleistocene peat deposits from sites in Greece (Tenaghi Philippon), in the British Isles and in Germany (Schöningen), using U-series, have been reported by Heijnis and Van der Plicht (1992). Their obtained ages for the Weichselian are in good agreement with the chronostratigraphy and TL dates. Some dates probably require corrections because of problems of undefined open-system behaviour of the peat. The organic deposits of the Schöningen warm event, for example, have been dated to between 180-227 ka (Heijnis, 1992, p.132).

[c] Potassium-Argon dating

The K/Ar- and Ar/Ar-methods are applicable to volcanic material and glauconite-rich sediments that are interbedded within other depositional sequences. Several dates are available from tephras interstratified with the Middle and Lower Rhine loess and terrace sequences, dealt with in more detail in chapter 5. They are related to different phases of volcanic activity in the Eifel region, which started at about 570 ka (Frechen & Lippold 1965) or probably even earlier, before 650 ka (Van den Bogaard and Schminke 1990). The tephras provide geochronological control within key-stratigraphical sequences, such as those from Kärlich and Ariendorf (Van Kolfschoten and Turner 1996) and confine the age of fluvial sequences further downstream of the river Rhine.

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[1] *Since the establishment of the modern Ice Age concept by Penck (1879) and Geikie (1895) among others (section 1.3.1).*

[2] *= Gippingian.*

[3] *Because of the authoritative status of the Alpine model one may (even) state that at least up to the 1950s a kind of reinforcement syndrom existed whereby apparent incompatibility and discrepancies (simply) were not considered or accepted because it would bring on too much confusion.*

[4] *Co-controlling accommodation space, sediment supply, grain-size and sedimentary processes.*

[5] *The Alpine glacial stages, for example, are still widely used in many mountaineous regions.*

[6] *Palaeotemperature ranges intimately related to the effect of precipitation.*

[7] *For example that cf. Köppen's classification.*

[8] *cf. Bowen 1978.*

[9] *Abbreviations are explained in section 3.4.3.*

[10] *Although they are relatively small-scale compared to subseries of pre-Quaternary systems.*

[11] *An age of 812 ka has been proposed for the Brunhes/Matuyama boundary (Langereis et al. 1997), based on rock-magnetic and geochemical properties from marine hemipelagic sediments with intercalated sapropel and tephra layers in the Ionean Sea.*

[12] *Till is a glacial diamicton and generally is only used as a genetic term.*

[13] *Downcutting of new channels and glacial basins and river diversion.*

[14] *Dumping of major sediment masses to form moraines, sandrs, kames and kettle holes.*

[15] *Typical leached soil types are 'brown earth', 'parabraunerde', 'braunlehm' and 'rotlehm' with clay-enriched B-horizons.*

[16] *Since solifluction is not necessarily confined to cold climates, the term 'gelifluction' has been proposed to describe solifluction associated with frost action (e.g. Washburn 1979).*

[17] *Requiring polar climates where mean annual temperatures are below -20 C respectively -80 C.*

[18] *Although faunal diversity was relatively high in the mammoth steppe in Alaska (Guthrie 1990).*

[19] *The enamel differentiation quotient (SDQ-value) of Arvicola molars decreases during the late Middle Pleistocene. This trend is used for correlation purposes.*

[20] *TL: Thermoluminescence, OSL: Optical Stimulated Luminescence, IRSL: InfraRed Stimulated Luminescence, GLSL: Green Light Stimulated Luminescence*

Chapter 4

A SUPPLEMENTARY STRATIGRAPHICAL FRAMEWORK FOR NORTHWEST AND CENTRAL EUROPE ON THE BASIS OF GENETIC SEQUENCE AND EVENT STRATIGRAPHY

Having reviewed the contemporary Middle Pleistocene stratigraphy of Northwest and Central Europe by discussing five broad categories of environments and their sedimentary products, they are now placed into a framework of interregional extent and significance. Such a large-scale framework requires a material basis from the type localities and type regions with uniformly defined units for interpretation. Since the existing (national) classification systems are based on different criteria, a supplementary, non-interpretive stratigraphical framework is advocated in this chapter in which the existing litho-, bio-, soil- and other stratigraphical elements have been integrated into local- and regional-scale units recognised and defined on the basis of bounding unconformities and depositional environment. These are used as event markers for palaeoclimatic reconstruction and interregional correlation.

4.1 Main natural type regions of Northwest and Central Europe

4.1.1 Geotectonic type regions

Sedimentary sequences are best compared within natural type regions that can be distinguished on the basis of morphology, geotectonic structure, regional substrate and drainage characteristics. The present-day topographical mosaic of high- and low-relief areas[1] in Northwest - and Central Europe, i.e. the broad distribution of mountain areas, basins and valleys (*Fig. 4.1*), is largely controlled by long-term tectonic processes which were active during different geological epochs. The basement of the geotectonic framework is formed by the tectonic and morphological highs of the Pre-Cambrian Baltic Shield / Fennoscandian High and the Palaeozoic Caledonian and Variscan Massifs (legend unit 1 in *Fig. 4.1*). Between these tectonic blocks in the European upland areas are (former) sedimentary basins and graben systems situated filled with younger Mesozoic and Cenozoic deposits.

Regional tectonic histories will not be discussed here in detail. Only the three most important tectonic events (of 1st and 2nd order cyclicity), active during the Mesozoic and Cenozoic Eras[2], are briefly discussed:

- The Alpine orogeny, comprising the upthrusting of the Alps and the Carpathians in several phases. The highlands of the Alpine foldbelt roughly form the European water divide. The northern Alpine foreland (nAF) and the Carpathian foreland (CF) are large-scale basins, resulting from the upthrusted Alpine fronts in which thick Tertiary sediments were deposited. Some important large-scale subsidence basins south of these mountain ranges are the Po Basin (PoB), the Vienna Basin (VB) and the Pannonian Basin (PnB).
- The opening of the North Atlantic and associated opening of the Northwest European Basin during the early Tertiary, resulting in continued large-scale subsidence along a NW-SE axis concentrated in the Central North Sea. Subsequent differential subsidence led to the origin of several sub-basins in the North Sea Basin which have acted as main Pleistocene depocentres, such as the Central Graben, the Sole Pit and three composed subbasins in the southern part of the North Sea Basin: the Anglo-Dutch (Broad Fourteens, Western Netherlands), the North German and the Polish sub-basins. The eastern part of the Northwest European Basin was only marginally influenced by tectonics during the Pleistocene.
- The continued activity of rift structures in the Central European uplands in between the North Sea Basin and the Alps (Ziegler 1994). Examples of these medium-scale areas in Northwest and Central Europe, showing disruption into grabens and horsts, are given in *table 4.1*. Some of these tectonic movements are accompanied by volcanic activity which continued into to the Pleistocene (e.g. in the Neuwied Basin and in the Eger Graben).

The complex geotectonic structure of the western part of Europe is in contrast to the rather homogeneous subsurface geology of the Pre-Cambrian East European Platform, comprising among others the Polish Platform and the Russian Plain. The latter extensive region has been relatively stable since and is covered by a relatively thin Pleistocene succession.

4.1.2 Distribution of Pleistocene sediments

Pleistocene sedimentation, climate and environment is superimposed on the geotectonic framework of the European continent briefly presented above. Whereas the type regions in the highlands and uplands are generally related to areas of uplift and erosion, thickest Pleistocene accumulations are found in the large- and medium-scale sedimentary basins of the European lowlands. The Pleistocene sediments normally rest on Tertiary sequences and depict the continuation of the Cenozoic geological development.

The formation and distribution of Pleistocene sediment types within the different type regions is related to depositional environment and source area. Wide-spread events, of 4th order cyclicity, related to climatic change, such as glaciations, marine transgressions and loess deposition, have left significant sequences. The longest sequences, whether they be interrupted by hiatuses or continuous, are predominantly found in areas which have not suffered the strongly erosional effect of sporadic glaciation, i.e. in the extraglacial areas. This allows further subdivision of the geotectonic regions into glaciated areas and non-glaciated areas in which a zonal latitudinal aspect can be seen. A further distinction can be made on the basis of the source areas of the sediments that filled the basins. Source areas comprise the centres of glaciation within the glaciated areas and the drainage basins of the large river systems. These subdivisions are important for the lithostratigraphical subdivision, for example, with regard to the petrographical and mineralogical characteristics of the deposits.

There are, however, differences between depositional environments that have prevailed. Fluvial, glacial and marine sequences, which dominate the infill of most large- and medium-scale basins, are the product of dynamic and erosional environments, i.e. they

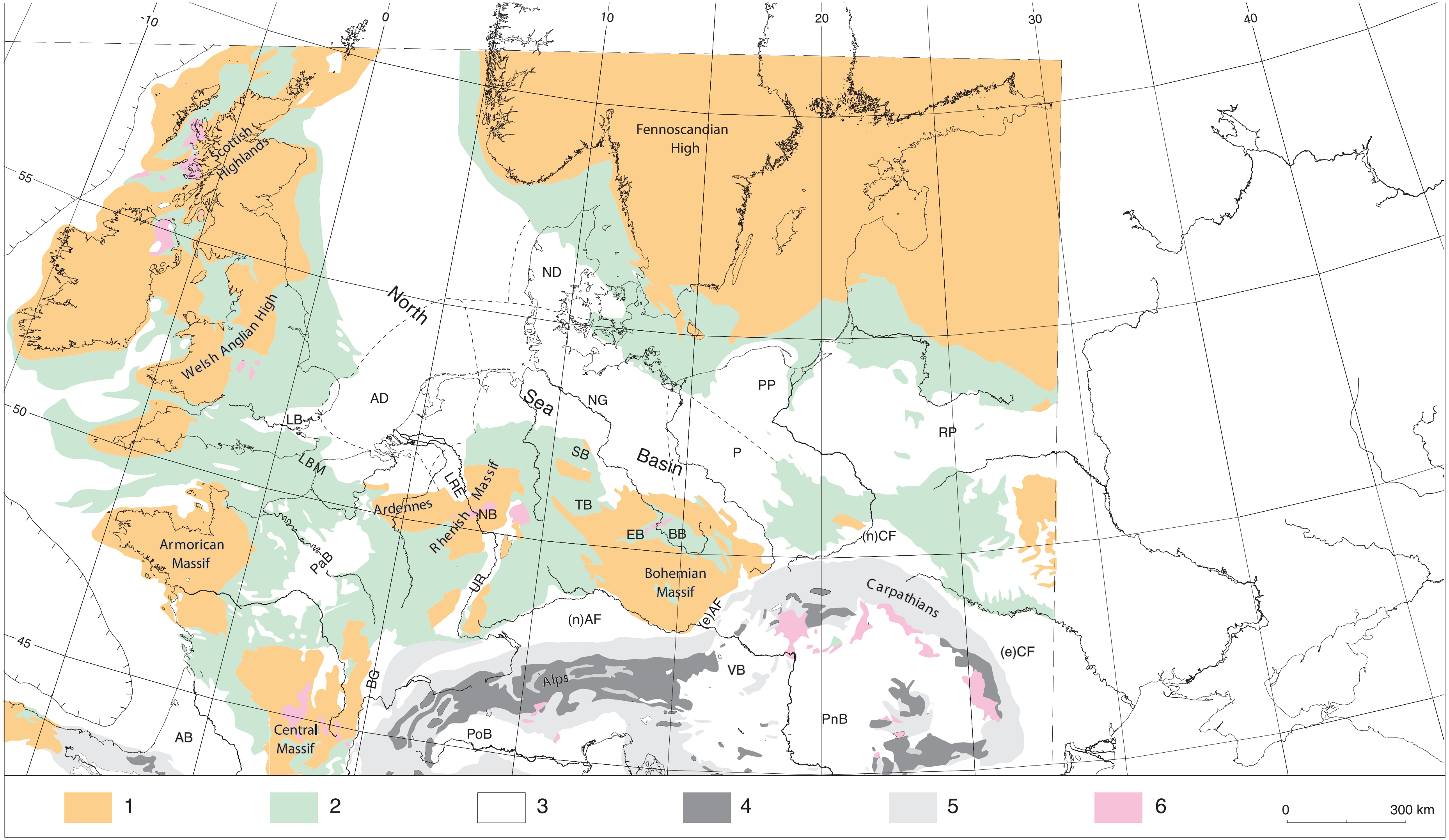


Figure 4.1 Location map showing the main geotectonic type regions in Northwest and Central Europe featuring Mesozoic and Cenozoic large- and medium-scale sedimentary basins (from Geological Map of Europe, BGR/Unesco). 1. Precambrian, 2. Mesozoic, 3. Cenozoic basins and sub-basins, 4. Alpine orogenic fold belt, 5. Alpine nappes, 6. Quaternary volcanic rocks. Abbreviations are explained in table 4.1.

comprise many unconformities. Their preservation potential is governed by rates of subsidence and sedimentation.
Small-scale basins and depressions within each geotectonic type region may occur as a result of (salt) tectonics, solution and karst processes, volcanic activity[3] and processes associated with glacial, cryogenic, fluvial and aeolian erosion[4] (*section 3.2.5*). They are generally important local sediment traps recording (semi-)continuous sedimentation and biological productivity. They have a high preservation potential but often are time-restricted.

The combination of the nature of Pleistocene sedimentary sequences on the one hand, and morphology, subsurface geology and tectonic structures on the other, allows a distinction of the following type regions and subregions in Europe:

	Non-glaciated type areas (from W to E)	Glaciated type areas
Large- and medium-scale lowland basins:	Paris Basin (PB),	Southern North Sea Basin:
	Lower Rhine Embayment (LRE),	-Anglo-Dutch North Sea subbasin (AD-NS)
	Pannonian basin (PnB):	-North German North Sea basin (NG-NS)
		-Polish North Sea basin (P-NS) or Polish Through
		Münsterland basin
		Danish Basin (ND)
		Oslo Graben
		Polish Platform (PP) incl. the Klestow graben
		Russian Plain (RP)
Large- and medium-scale upland basins:	Neuwied Basin (NB)	London Basin (LB)
	Leine Graben	Münsterland Basin,
	North Bohemian Basins (BB)	Hessian Depression
	Eger Graben (EB)	Subhercynian basin (SB)
	Upper Rhine Graben (URG)	Thuringian basin (TB)
	easternmost part of northern Alpine foreland basin (e-AF)	Carpatian foreland (CF): subdivided into a northern and eastern part
	Bresse Graben (BG)	Northern Alpine foreland (n-AF), subdivided into a western part, central part and an eastern part.
Upland (geotectonic) areas/highs	British Highs (Welsh-Anglia High, Pennine High, Scottish Highlands)	Vosges Mts.
	Armorican Massif	Black Forest Mts.
	Massif Central	Harz Mts.
	Ardennes and adjacent London Brabant Massif (LBM)	Jura Mts.
	Rhenish Massif (Hunsrück, Westerwald, Taunus, Eifel)	the Alps (Central, Western, Eastern)
	Thuringian Forest	Carpatians
	Flechtinger High	Holy Cross Mts.
	Osning zone	
	Bohemian Massif	

Table 4.1: Geotectonic subdivision of Northwest and Central Europe and Quaternary sediment type areas.

4.2 Building components of the genetic sequence stratigraphical framework for the Middle Pleistocene terrestrial record of Northwest and Central Europe

4.2.1 Wide-spread unconformity-bounded units and genetic sequences

The European mid-latitude type regions have repeatedly been supplied with large amounts of similar allochtonous sediments which can be correlated over long distances. These wide-spread sedimentary units, including their basal unconformities, largely extend beyond local and regional controls. The following wide-spread genetic sequences, eligible for interregional palaeoclimatic and global land-sea correlation, are further discussed in this section:
[a] Glacial sequences,
[b] Subaerial aeolian (loess) sequences,
[c] (Coastal) marine sequences.

The chronostratigraphical positions of these main building blocks of the European Pleistocene stratigraphy are starting points for further interregional correlation.

[a] Glacial synthems and sequences

Glacial sequences comprise tills, glaciofluvial and glaciolacustrine sediments (*section 3.2.1*) that reflect different phases of an ice-sheet expansion: advance or transgressive phase, maximum extension/limit, deglaciation or regressive phase to which different sub-phases may be added. In mid-latitude Europe they originated from the most extensive Pleistocene ice-sheet expansions from three major glaciation centres5: Fennoscandia, Britain and the Alps. On a regional scale they form synthems representing a (sub)cycle of glacial deposition bounded by erosional unconformities which may be further subdivided into several subsynthems (*Fig. 4.2*).

The base of a glacial synthem is formed by the 'transgressive glacial surface' and the 'maximum limit surface' in the ice-margin zone. The latter is generally recognised by sand and gravel sandurs, glaciolacustrine clay and silt or dislocated sediments of moraine ridges, deposited in proglacial/ice-marginal position. In a proximal direction till units may characterise the base of a glacial sequence/synthem/formation. These different sedimentary units represent (transgressive) glaciation maxima which can be regionally subdivided into unconformity-bounded lithofacies units of glacial depositional subenvironments, e.g. subglacial till beds and moraine complexes related to ice-sheet marginal positions.

In the scheme of *figure 4.2* all glacial synthems associated with the Fennoscandian, British and Alpine glaciations are grouped into genetic sequences representing the preserved sedimentary evidence of the major glaciation cycles. A glacial sequence thus represents one or more synthems that can be attributed to a major cycle of ice-sheet expansion and decay related to a centre of glaciation. Glacial sequences provide relative stratigraphical control to local and regional non-glacial sequences in the glaciated type areas (*Fig. 4.7*) which can be indirectly matched with the global ice-volume fluctuations in the MIS record. The Fennoscandian Saalian glacial sequence comprises the Drenthe-1, -2 and Warthe synthems in the North Sea basin type areas, the Odra and Warta synthems in Polish Platform type area and the Dniepr and Moscow synthems on the Russian Platform. The Fennoscandian Elsterian glacial sequence, and coeval British Anglian glacial sequence, generated the first widespead glacial synthems into the Northwest European lowlands and adjacent upland basins, such as the Subhercynic basin and the Thuringian basin. Together with equivalent glacial sequences from Eastern Europe, they are grouped into a sequence comprising the Peelo, Lauenburg, Elster 1 and Elster 2 synthems in the type regions of the North Sea basin, the San 2/ Wilga synthems in the Polish Platform type area and the Oka synthem in the Russian Plain. Regionally, till beds, glaciolacustrine clays and push moraine complexes are distinguished as unconformity-bounded (sub)units. Evidence of pre-Elsterian glaciations is only found in Northeastern and Eastern Europe and offshore Norway (Ehlers *et al.* 1999) which are grouped into a Fennoscandian Donian glacial sequence.

Terminology: glacial synthems are here informally named after their type locality and dominant lithofacies assemblage or morphological position: e.g. Drente Till synthem, Warthe moraine synthem. The glacial sequences are informally named after the centre/source area of an ice-sheet with reference to the regionally known stratigraphical code: e.g. Fennoscandian Donian, Elsterian/ Sanian/Okian, Saalian/Dniepr and Weichselian/Valdai glacial sequences. The sequences are related to glacial depositional cycles which, similar to the sedimentary cycles in the loess sequences (Kukla 1970), are labeled by capital letters: e.g. Fennoscandian glacial cycle C which corresponds to the Central European loess sequence in cycle C.

[b] Subaerial loess synthems and sequences

Loess deposits, loess-like deposits, cover sands and a variety of denudational deposits are subaerial deposits which are commonly found in the extraglacial areas. They are concentrated on the lee sides of river valleys, in basins and on plateaux in the Central European uplands up to altitudes of about 700 m. Sedimentary units in between erosional and/or subaerial unconformities representing cycles of subaerial deposition are here classified as synthems or subsynthems, depending on their regional extent and significance. Loess synthems may locally be interrupted by subaerial lithofacies associations consisting of colluvial or soliflual deposits, i.e. weathering products from hill slopes. On a regional scale, loess synthems can be classified sequence units comprising (4th order) cycles of loess deposition under cold, dry climate conditions. Loess sequences on river terraces generally start with local-scale synthems comprising denudational deposition, indicating more humid conditions prior to loess deposition, and may contain minor subaerial unconformities, reflecting climatic oscillations. In their upper part they show leaching and soil formation of Bt-types.

Subaerial aeolian (loess) sequences in the non-glaciated type regions of Central and Western Europe (*Fig. 4.3*), are associated with periglacial deserts. Their succession at first corresponds with the continental loess reference records available from Eurasia and China, in which eight Middle and Late Pleistocene 4th order sedimentary cycles have been identified, although loess accumulation rates may vary. The character of the subaerial intervals between the Chinese plateau loess and the European valley slope loesses differs, however, and the latter has to be considered at smaller (local) scales. Dating of most of the loess units in the European uplands is confined by the fluvial terrace systems on which they predominantly rest.

The most suitable reference record for the the loess/palaeosol sequence is that of Červený Kopec in Slovakia (*figures 2.2* and *3.2*). Kukla (1969, 1970) was the first to link the sedimentation cycles in loess sequences in the easternmost foreland basin of the Alps (e-nAF: table 4.1) with the climate-proxy oceanic record (*section 3.1.1*). Cycles A to I represent interglacial-glacial cycles within the Brunhes Chron polarity zone, most of which include several second-rate climatic oscillations. These nine sedimentation cycles are covering four different terrace levels (CK1 up to CK4) of the Morava river system that is part of the middle course section of Danube river basin. Kukla and Çilek (1996) also distinguish 'megacycles' in this Pleistocene loess/palaeosol succession overlying each terrace surface: megacycle I includes loess cycles A to C, megacycle II loess cycles D to F, megacycle III loess cycles G to H and megacycle IV the loess cycles I to K.

Terminology: subaerial synthems are here informally named with reference to the type locality, eventually further subdivided into lithofacies units representing a major (local) depositional cycle, e.g. Kärlich HII loess synthem. The subaerial aeolian sequence units are informally named after the river section or tectonic basin and the regionally known stratigraphical code, e.g. Middle Rhine Kärlich H subaerial sequence.

[c] (Shallow sea and coastal)marine synthems and sequences

Shallow marine or paralic sequences mainly consist of sandy and clayey lithofacies associations. In coastal marine sequences also beds of reworked gravels and shells may be incorporated. Synthems within a marine sequence represent depositional cycles that are regionally distinguished on the basis of bounding unconformities.

Marine sequences on the continental shelf areas of Northwest Europe (shown in *Fig. 4.4*) represent transgressional-regressional phases associated with worldwide glacio-eustatic sea-level fluctuation cycles of the fourth order. Two additional factors that play a significant role in the sequence building of basins are tectonics6 and sedimentation rates. In strict sequence stratigraphical terminology these lower order cycles, e.g. the building of the fluvial-deltaic plain in the North Sea basin, form the sequences. In areas of long-term subsidence like the North Sea basin, where sedimentation prevails, evidence of former transgressions is found in superposition. The transgression-regression cycles, each cycle of fall and rise bounded by subaerial unconformities, represent 'parasequences'. On land, at the margin of the basins, parasequence boundaries are formed by the maximal flooding surface and consist of relatively conformable successions of genetically related beds, such as the North Sea Holsteinian and Eemian deposits. Since the shelves of the present-day seas of Northern Europe have been glaciated, their stratigraphy is complicated by interruptions of the marine sequences by glacial and subaerial synthems. During low sea-level stands erosion and reworking dominates, forming the bounding surfaces of the synthems.

The Middle Pleistocene sea-level fluctuations in the North Sea basin are not only related to glacio-eustatic processes superposed on 3rd order subsidence cyclicity. Glacio-isostatic rearrangements in and marginal to the formerly glaciated areas have for long been recognised and have, for example, been used as an argument for the far inland extension of marine transgressions in the Northwest European lowlands following the major Fennoscandian glaciations (Sarnthein *et al.* 1986, Zagwijn 1992). Marine terraces found along non-glaciated coasts, e.g. in the Channel, as well as those in the Mediterranean and Black Sea type regions, are separate synthems which have been uplifted by long-term tectonics.

Terminology: shallow sea and coastal marine synthems are informally named here with reference to their type locality and according to the lithofacies assemblage within their bounding surfaces: e.g. Eem marine sand and clay synthem. The marine sequences are informally here named after the sea margin present in the type region and regionally known stratigraphical code: e.g. Anglo-Dutch North Sea (AD-NS) Eemian marine sequence, Channel Herzeele I marine terrace sequence.

4.2.2 Regional-scale unconformity-bounded units and genetic sequences

[a] Fluvial synthems and sequences

Fluvial sequences contain many unconformities. Lithofacies assemblages within unconformities of regional significance and comprising one aggradational cycle are distinguished here as synthems. Lithofacies assemblages may point to braided, coarse-grained, or to meandering, fine-grained, river channel systems. Petrographical composition, including heavy minerals, may relate to changes in drainage patterns or to glacial or volcanic sources. Lithofacies changes are largely determined by cold respectively warm climate conditions. Nevertheless, climatic interpretations based on local fluvial synthems are not straightforward and must be supported by other stratigraphical evidence, such as palaeontological data or structural features.

Both terraced and superimposed fluvial aggradational sequences reflect that river activity is highest during cold climate conditions. Main aggradation phases generally occurred at the transitions to and from warm vegetated periods. Main downcutting phases to a lower erosion base level occurred during the cold stages featuring low sea-level stands, permafrost and dry desert conditions beyond the expanding ice-sheets. The basal coarse-grained parts of fluvial sequences in the middle river sections then represent aggradation as a result of ameliorating climate conditions during the deglaciation phase. The coarse-grained upper parts are deposited when vegetation cover in landscapes decreases (again) under prevailing cold climate conditions. They may cover preserved fine-grained lithofacies units from warm-stage type channel systems. This general model seems valid for most of the Middle and Upper Pleistocene terrace successions in river sections draining non-glaciated (upland) areas and not receiving glacial meltwaters. The Seine and Somme rivers in the Paris Basin, the river Meuse, the post-Anglian Thames and many tributaries of the Rhine, Elbe and Danube, comprise terrace series which apparently record the 100 ka climatic cyclicity from the last 700 ka without remarkable irregularities in vertical erosion steps.

The structure and preservation of aggradational terrace sequences in response to (cold) climate-driven events is different in river sections affected by glaciation and by interference of regional geotectonic variability. Fluvial sequences in the glacially affected river sections, such as the lower reaches of the Rhine, Weser and Elbe, as well as the rivers draining the northern Alps (upper Rhine and Danube) and the Russian Plain (Dniepr, Don) are mainly build of proglacial aggradation and often only allow subdivisions of terrace sequence groups, forming supersynthems, intermediate between extensive glaciations (*section 4.3.2*). The role of regional geotectonic variability is further discussed in *section 4.3.3*.

Terminology: fluvial synthems are here informally named after their type locality with reference to the dominant lithofacies units and/or morphological position of an aggradation cycle. Superimposed (stacked) synthems in sedimentary basins are termed alluvial synthems, e.g. Urk I sand synthem representing one of the different sedimentary units in the Urk Formation. Their identification is mainly based on borehole information. Vertically separated synthems along river valley slopes are termed terrace synthems, e.g. Leubsdorf gravel terrace synthem. Fluvial sequences of regional extent are informally named here after the drainage basin or

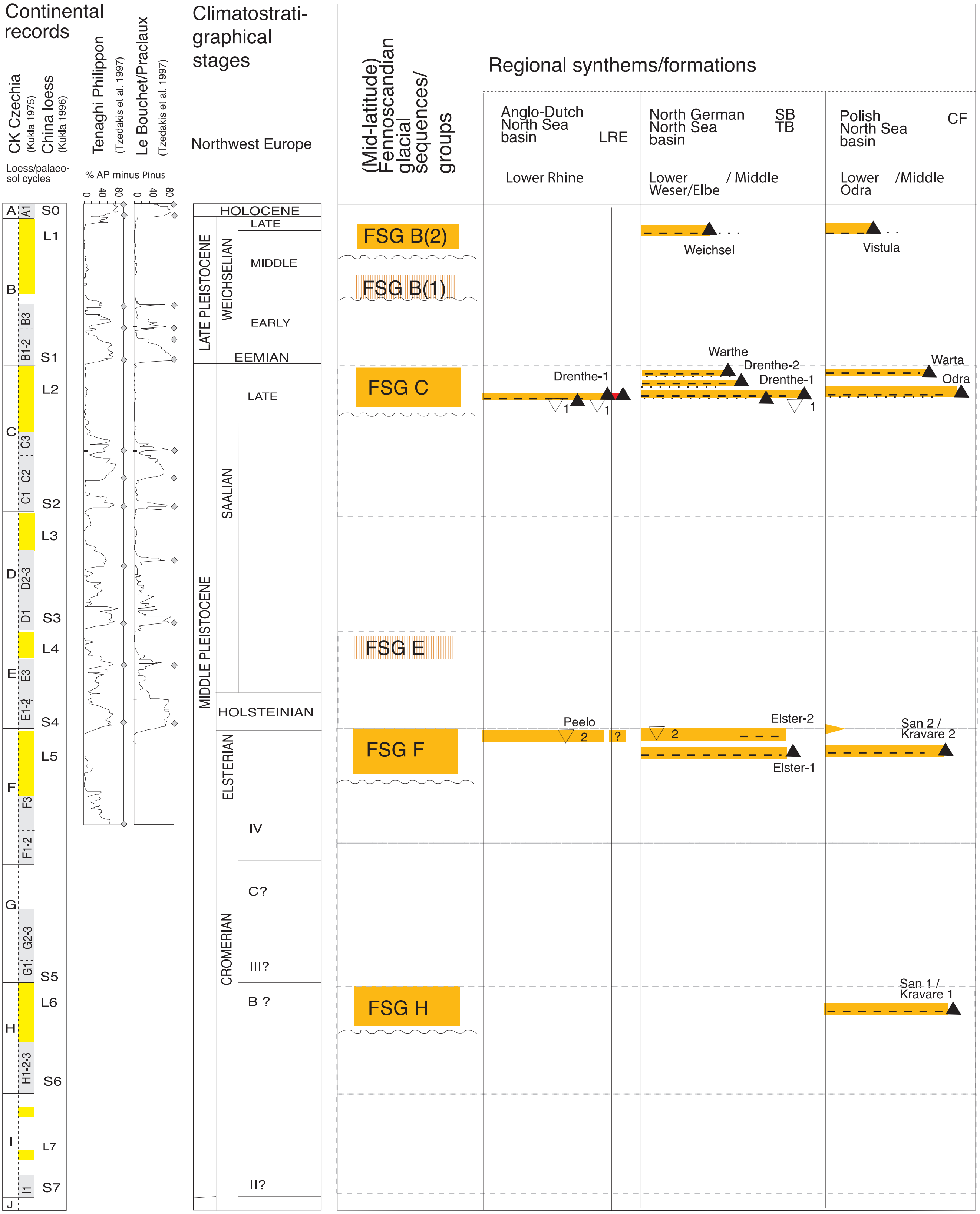


Figure 4.2 Continent-wide and regional subdivision of Middle and Late Pleistocene glacial synthems and sequences for Northwest and Central Europe. Nomenclature is tentative and largely follows existing unit names.

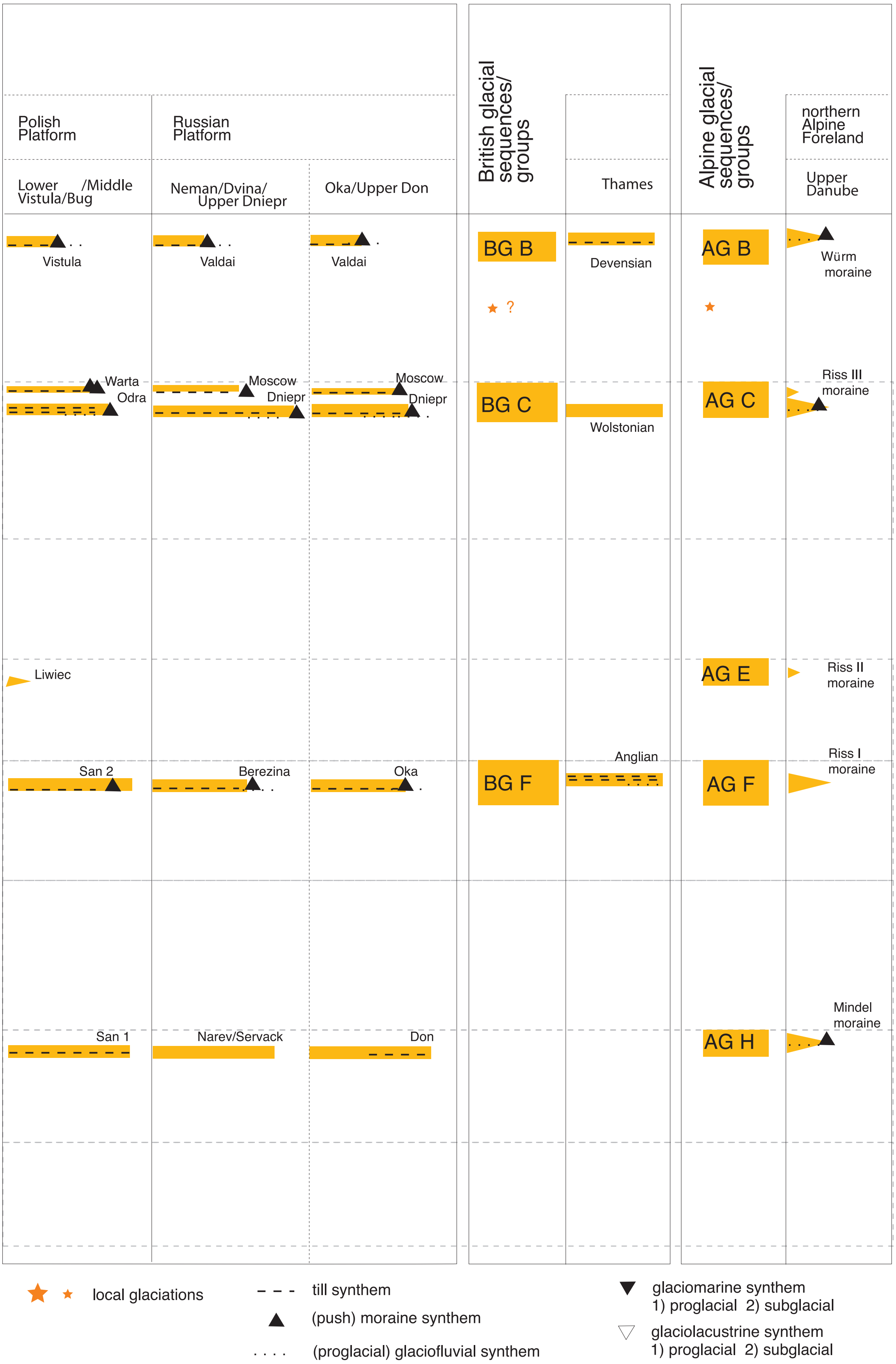
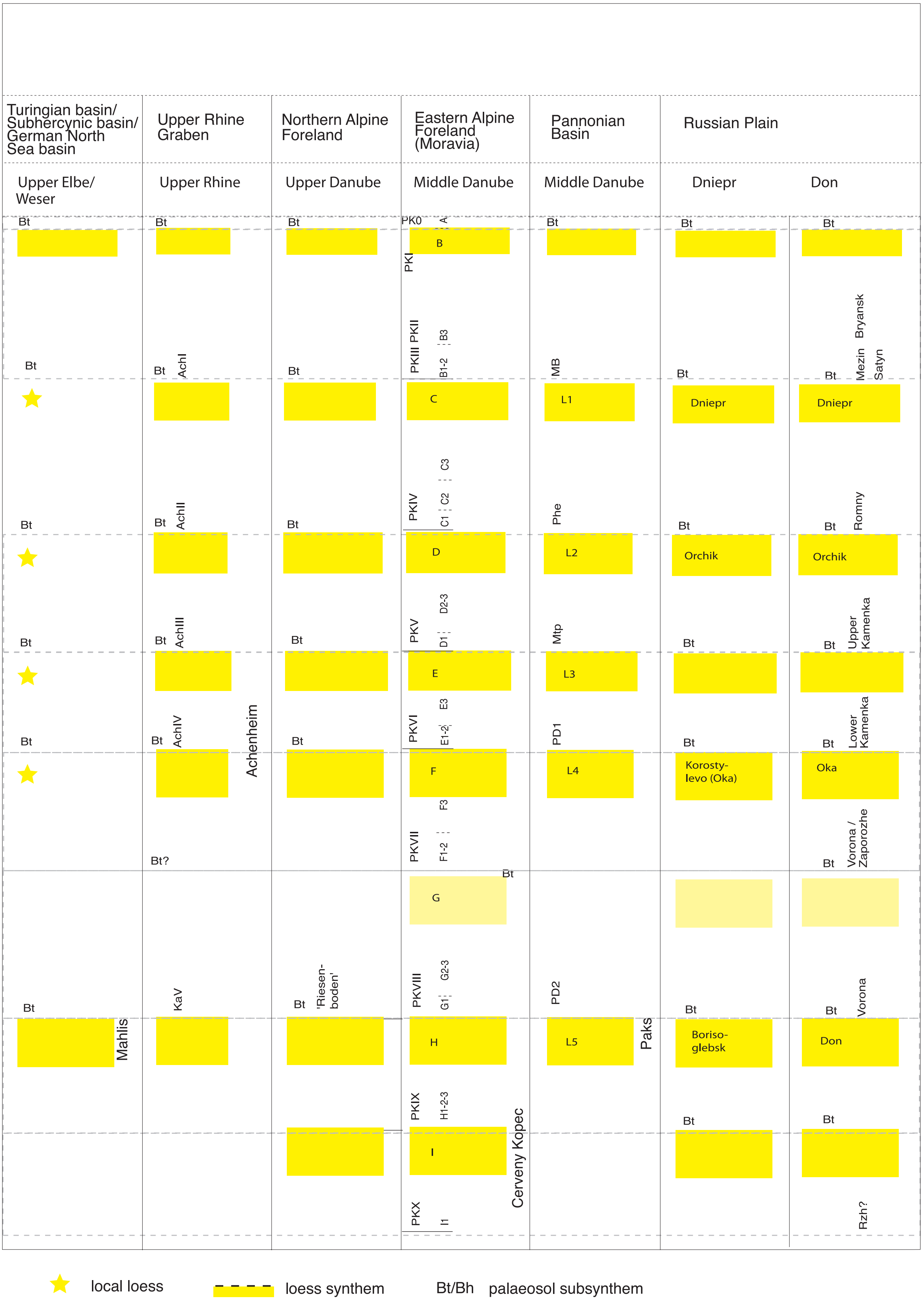

Polish Platform
Russian Platform
British glacial sequences/ groups
Alpine glacial sequences/ groups
northern Alpine Foreland
Lower /Middle Vistula/Bug
Neman/Dvina/ Upper Dniepr
Oka/Upper Don
Thames
Upper Danube
Vistula
Valdai
Valdai
BG B
Devensian
AG B
Würm moraine
?
Warta
Odra
Moscow
Dniepr
Moscow
Dniepr
BG C
Wolstonian
AG C
Riss III moraine
Liwiec
AG E
Riss II moraine
San 2
Berezina
Oka
BG F
Anglian
AG F
Riss I moraine
San 1
Narev/Servack
Don
AG H
Mindel moraine
local glaciations
till synthem
(push) moraine synthem
(proglacial) glaciofluvial synthem
glaciomarine synthem
1) proglacial 2) subglacial
glaciolacustrine synthem
1) proglacial 2) subglacial

Figure 4.3 Continent-wide and regional subdivision of Middle and Late Pleistocene subaerial periglacial synthems and sequences for Northwest and Central Europe. Nomenclature is tentative and largely follows existing unit names.


Turingian basin/ Subhercynic basin/ German North Sea basin
Upper Rhine Graben
Northern Alpine Foreland
Eastern Alpine Foreland (Moravia)
Pannonian Basin
Russian Plain
Upper Elbe/ Weser
Upper Rhine
Upper Danube
Middle Danube
Middle Danube
Dniepr
Don
Bt
Bt
Bt
PK0
A
B
PKI
Bt
Bt
Bt
Bt
Bt
Bt
AchI
Bt
PKIII PKII
B1-2
B3
MB
Bt
Bt
Bryansk
Mezin
Satyn
C
L1
Dniepr
Dniepr
Bt
Bt
AchII
Bt
PKIV
C1
C2
C3
Phe
Bt
Bt
Romny
D
L2
Orchik
Orchik
Bt
Bt
AchIII
Bt
PKV
D1
D2-3
Mtp
Bt
Bt
Upper Kamenka
E
L3
Bt
Bt
AchIV
Achenheim
Bt
PKVI
E1-2
E3
PD1
Bt
Bt
Lower Kamenka
F
L4
Korosty-levo (Oka)
Oka
Bt?
PKVII
F1-2
F3
Bt
Vorona / Zaporozhe
G
Bt
KaV
Bt
'Riesen-boden'
PKVIII
G1
G2-3
PD2
Bt
Bt
Vorona
Mahlis
H
L5
Paks
Boriso-glebsk
Don
PKIX
H1-2-3
Bt
Bt
I
Cerveny Kopec
PKX
I1
Rzh?
local loess
loess synthem
Bt/Bh palaeosol subsynthem

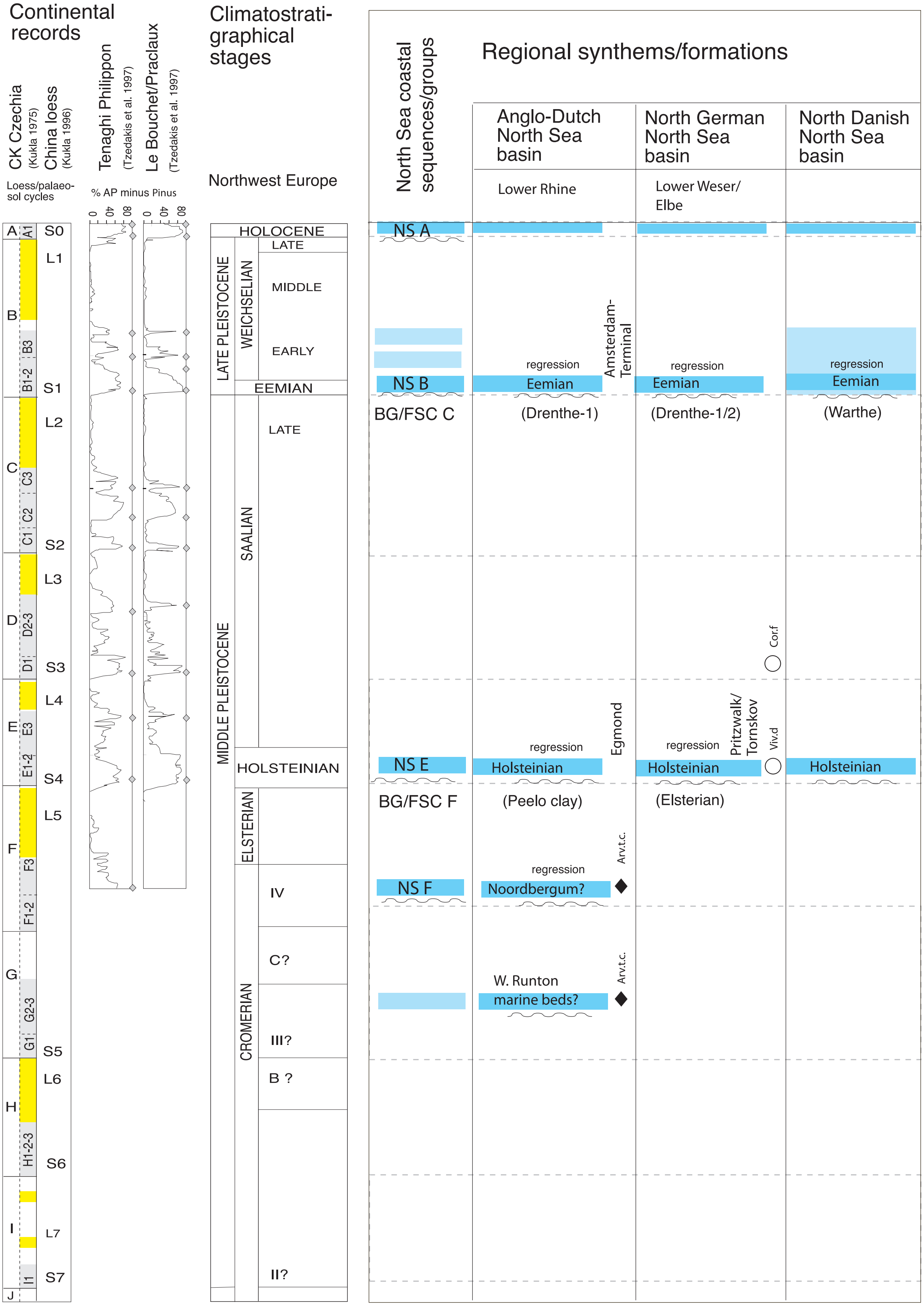
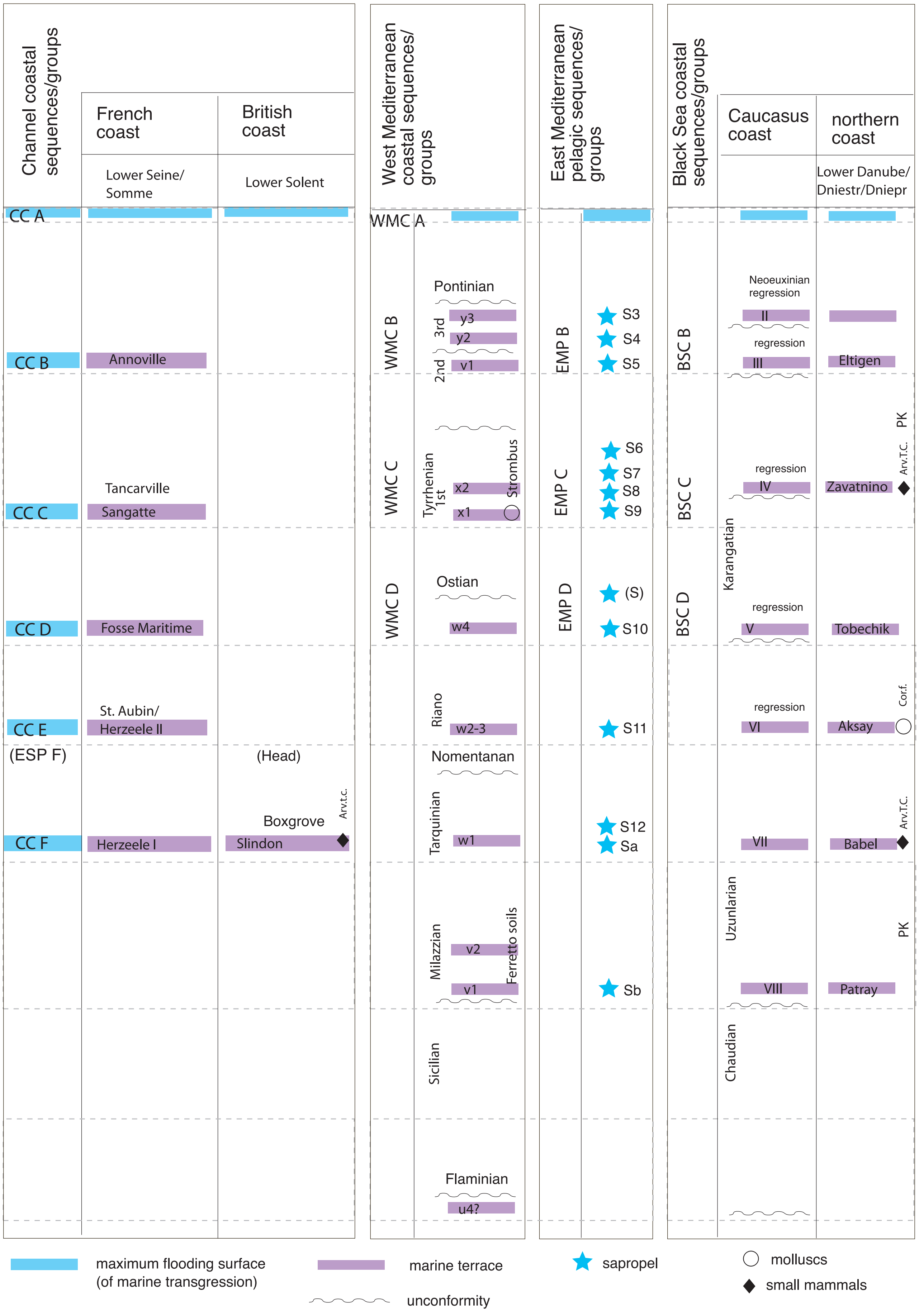


Figure 4.4 Continent-wide and regional subdivision of Middle and Late Pleistocene marine synthems and sequences for Northwest and Central Europe. Nomenclature is tentative and largely follows existing unit names.


Channel coastal sequences/groups
French coast
Lower Seine/ Somme
British coast
Lower Solent
West Mediterranean coastal sequences/ groups
East Mediterranean pelagic sequences/ groups
Black Sea coastal sequences/groups
Caucasus coast
northern coast
Lower Danube/ Dniestr/Dniepr
CC A
WMC A
CC B
Annoville
WMC B
Pontinian
3rd
y3
y2
2nd
v1
EMP B
S3
S4
S5
BSC B
Neoeuxinian regression
II
regression
III
Eltigen
CC C
Tancarville
Sangatte
WMC C
Tyrrhenian 1st
x2
x1
Strombus
EMP C
S6
S7
S8
S9
BSC C
regression
IV
Zavatnino
PK
Arv.T.C.
CC D
Fosse Maritime
WMC D
Ostian
w4
EMP D
(S)
S10
BSC D
Karangatian
regression
V
Tobechik
CC E
St. Aubin/
Herzeele II
Riano
w2-3
S11
regression
VI
Aksay
Corf.
(ESP F)
(Head)
Nomentanan
CC F
Herzeele I
Boxgrove
Slindon
Arv.t.c.
Tarquinian
w1
S12
Sa
VII
Babel
Arv.T.C.
Milazzian
v2
v1
Ferretto soils
Sb
Uzunlarian
VIII
Patray
PK
Sicilian
Chaudian
Flaminian
u4?
maximum flooding surface (of marine transgression)
marine terrace
unconformity
sapropel
molluscs
small mammals

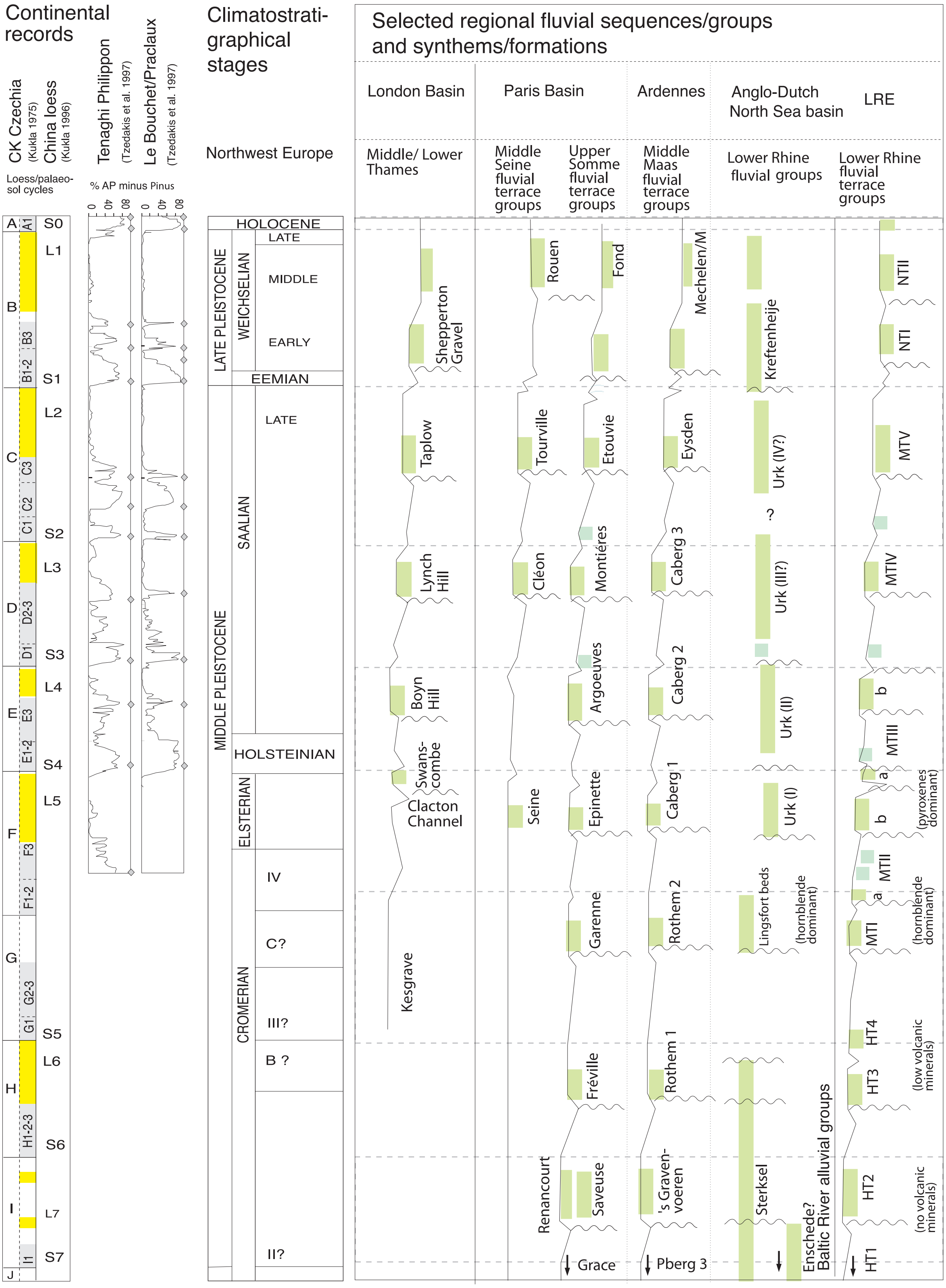
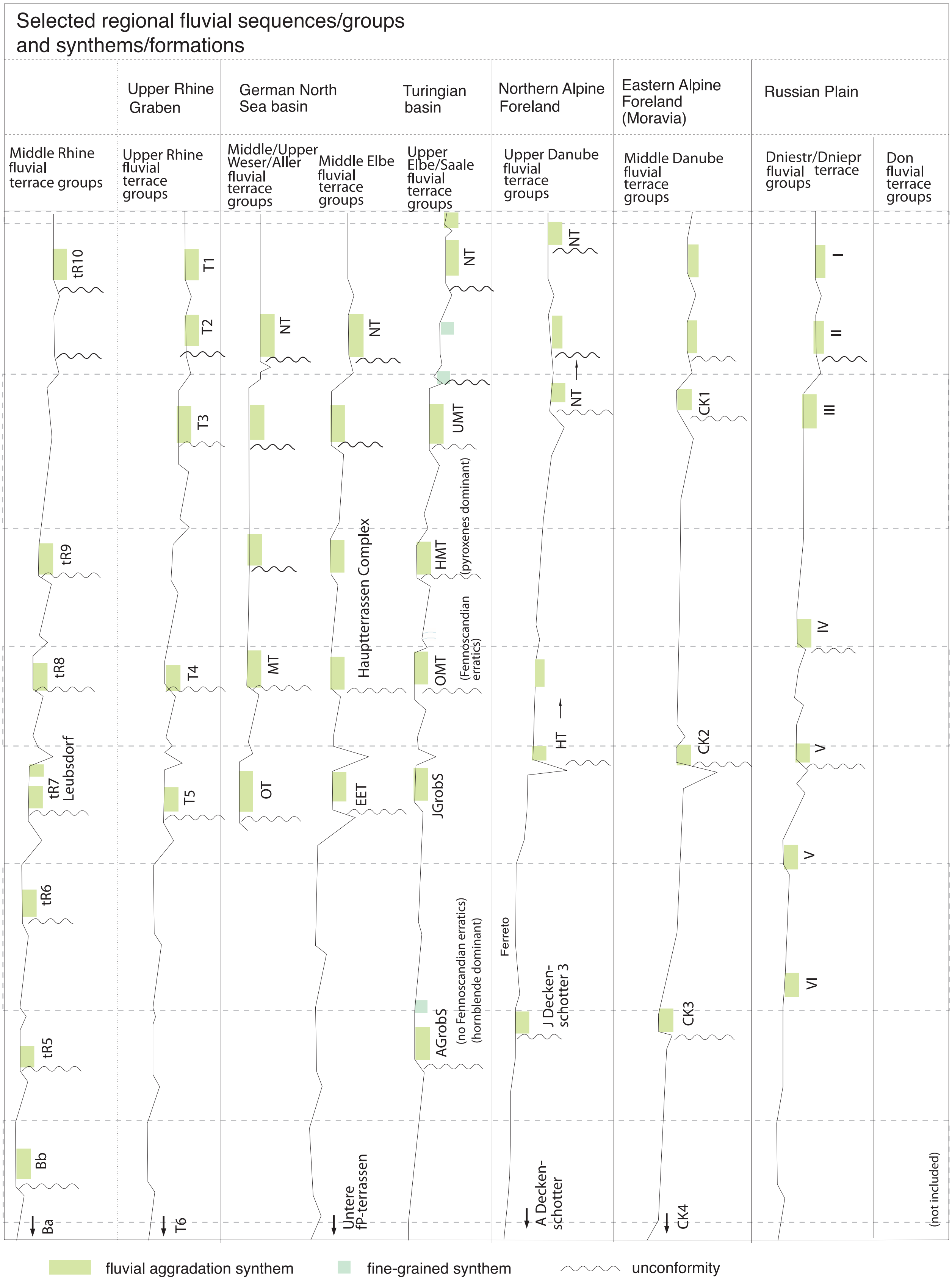


Figure 4.5 Continent-wide and regional subdivision of Middle and Late Pleistocene fluvial synthems and sequences for Northwest and Central Europe. Nomenclature is tentative and largely follows existing unit names


Selected regional fluvial sequences/groups and synthems/formations
Upper Rhine Graben
German North Sea basin
Turingian basin
Northern Alpine Foreland
Eastern Alpine Foreland (Moravia)
Russian Plain
Middle Rhine fluvial terrace groups
Upper Rhine fluvial terrace groups
Middle/Upper Weser/Aller fluvial terrace groups
Middle Elbe fluvial terrace groups
Upper Elbe/Saale fluvial terrace groups
Upper Danube fluvial terrace groups
Middle Danube fluvial terrace groups
Dniestr/Dnieper fluvial terrace groups
Don fluvial terrace groups
tR10
tR9
tR8
tR7 Leubsdorf
tR6
tR5
Bb
Ba
T1
T2
T3
T4
T5
T6
NT
MT
OT
NT
Hauptterrassen Complex
EET
Untere fP-terrassen
NT
UMT
HMT
(pyroxenes dominant)
OMT
(Fennoscandian erratics)
JGrobS
AGrobS
(no Fennoscandian erratics) (hornblende dominant)
NT
NT
HT
Ferreto
J Decken-schotter 3
A Decken-schotter
CK1
CK2
CK3
CK4
I
II
III
IV
V
V
VI
(not included)
fluvial aggradation synthem
fine-grained synthem
unconformity

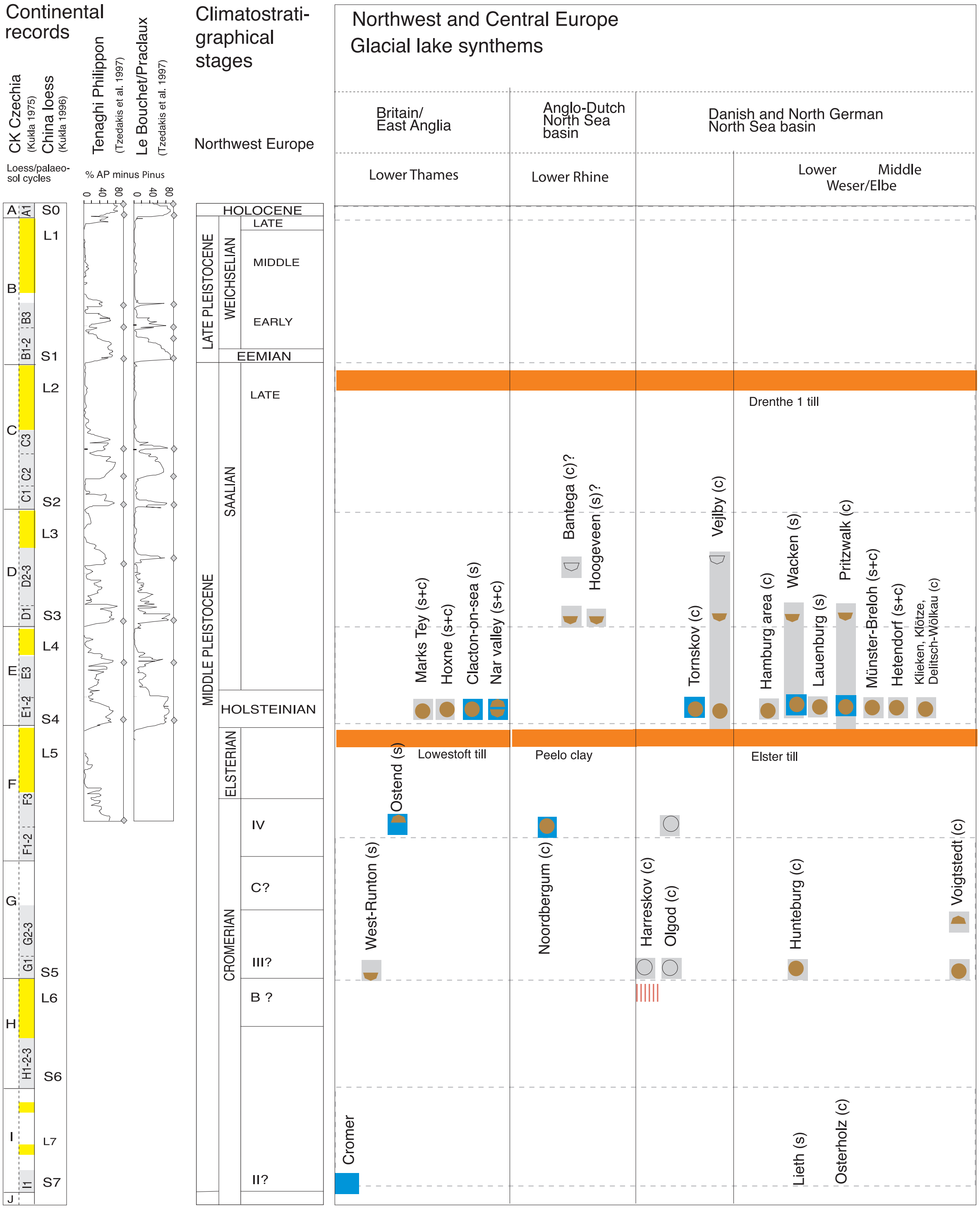
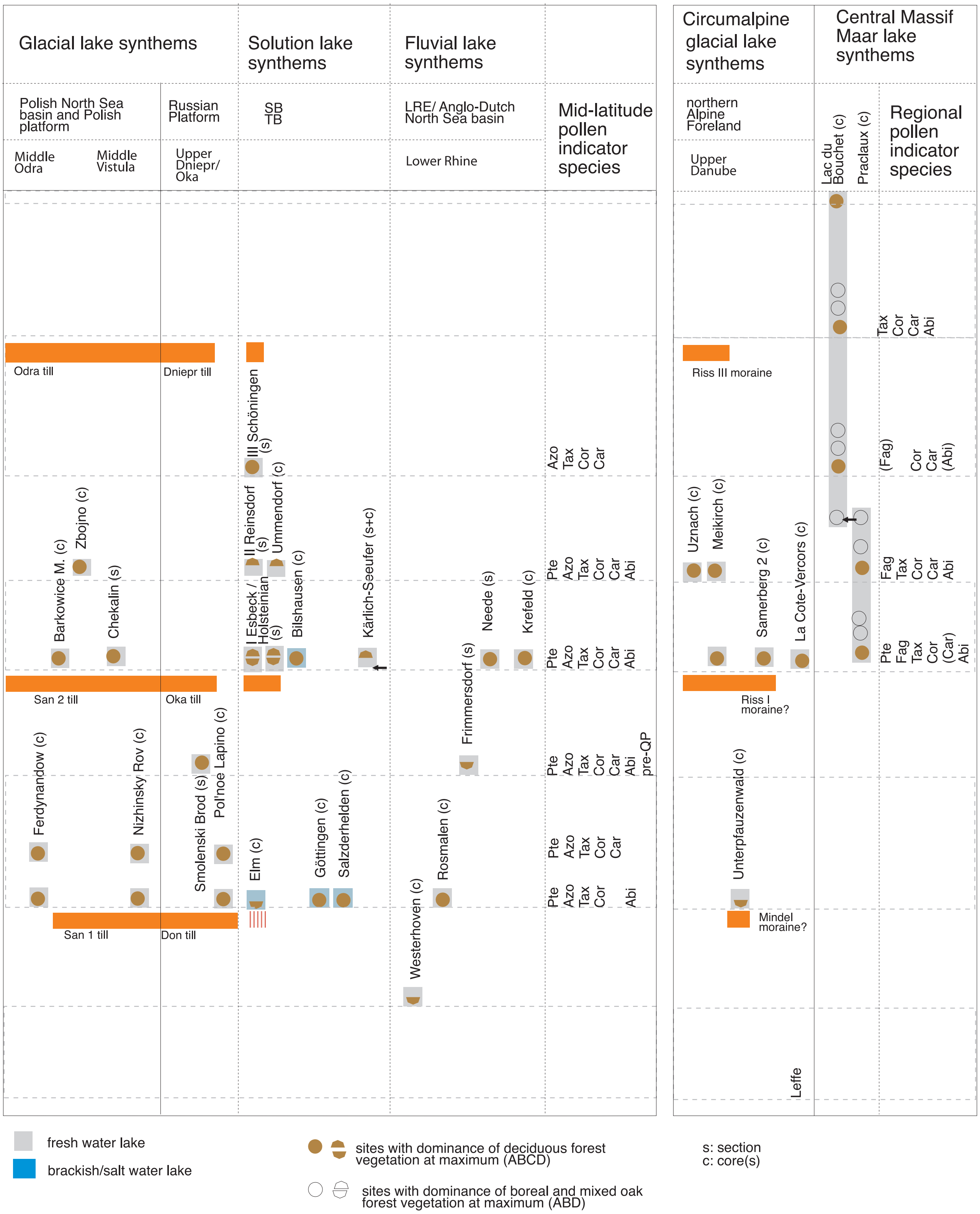


Figure 4.6 Continent wide and regional subdivision of selected Middle Pleistocene lacustrine synthems and sequences for Northwest and Central Europe. Nomenclature is tentative and largely follows existing unit names


Glacial lake synthems
Solution lake synthems
Fluvial lake synthems
Circumalpine glacial lake synthems
Central Massif Maar lake synthems
Polish North Sea basin and Polish platform
Russian Platform
SB
TB
LRE/ Anglo-Dutch North Sea basin
Mid-latitude pollen indicator species
northern Alpine Foreland
Regional pollen indicator species
Middle Odra
Middle Vistula
Upper Dniepr/ Oka
Lower Rhine
Upper Danube
Lac du Bouchet (c)
Praclaux (c)
Tax Cor Car Abi
Odra till
Dniepr till
Riss III moraine
III Schöningen (s)
Azo Tax Cor Car
(Fag) Cor Car (Abi)
Barkowice M. (c)
Zbojno (c)
Chekalin (s)
II Reinsdorf (s)
Ummendorf (c)
I Esbeck / Holsteinian (s)
Bilshausen (c)
Kärlich-Seeufer (s+c)
Neede (s)
Krefeld (c)
Pte Azo Tax Cor Car Abi
Uznach (c)
Meikirch (c)
Samerberg 2 (c)
La Cote-Vercors (c)
Fag Tax Cor Car Abi
Pte Azo Tax Cor Car Abi
Pte Fag Tax Cor (Car) Abi
San 2 till
Oka till
Riss I moraine?
Frimmersdorf (s)
Ferdynandow (c)
Nizhinsky Rov (c)
Smolenski Brod (s)
Pol'noe Lapino (c)
Pte Azo Tax Cor Car Abi pre-QP
Unterpfauzenwald (c)
Elm (c)
Göttingen (c)
Salzderhelden (c)
Rosmalen (c)
Pte Azo Tax Cor Car
Pte Azo Tax Cor Abi
San 1 till
Don till
Mindel moraine?
Westerhoven (c)
Leffe
fresh water lake
brackish/salt water lake
sites with dominance of deciduous forest vegetation at maximum (ABCD)
sites with dominance of boreal and mixed oak forest vegetation at maximum (ABD)
s: section
c: core(s)

river section in which they occur and their known stratigraphical code: e.g. Middle Rhine Middle Terrace 2 (MT2) sequence or Lower Rhine Urk alluvial sequence group.

[b] Subaerial non-aeolian synthems and sequences

Subaerial non-aeolian sequences are the most problematic ones to correlate over long distances since they are bound by local and regional factors including substrate, topography, physiography and tectonic activity. Soliflual and colluvial deposits generally fill depressions originating from erosion and subsidence and occur on and below slopes and escarpments. Nevertheless, some elements are very helpful in palaeoenvironmental reconstruction and chronostratigraphy since they contain detailed climatic information themselves and/or have protected underlying soil complexes and sequences from erosion.
Examples are the head deposits in Britain, Ireland and France, soliflual/colluvial deposits covering terrace surfaces, soliflual/colluvial levelling deposits in basins and small valleys throughout the region, e.g. the subaerial units Kärlich G I to G IV (*section 5.2.2*).

4.2.3 Local-scale unconformity-bounded units and genetic sequences

Next to sedimentological evidence fossils within the terrestrial sequences yield important palaeoclimatic information. Biological activity and organic production was abundant during non-glacial warm climate conditions. Their remains are incorporated and well preserved in local lacustrine and mire environments, next to and to a lesser degree in post-sedimentary soil complexes.

[a] Lake and mire synthems and sequences

The generally fine-grained lithofacies assemblages and organic deposits in lake sequences show less distinct internal unconformities than other sequences. The recognition of synthems, representing accumulation cycles related to lake level fluctuations and sediment influx, is therefore not always easy. In particular biostratigraphical evidence is of great help in distinguishing lake sequences representing major climatic cycles. When stratigraphical control of such local sequences is ascertained, e.g. glacial lake sequences, their palynological records are of concern in the dating and interregional correlation of Middle Pleistocene cold and warm palaeoclimatic stages. The stratigraphical position and early vegetational development of the glacial lake sequences formed in relics of depressions left behind after the Elsterian/Anglian glaciations, generally is undisputed and recognised over wide areas. Their development in the European lowlands starts with the same lithological conditions and therefore are very uniform. Anomalies may be due to local hydrological and geological (substrate, soil) conditions, such as differences in lake status and drainage conditions. Vegetation cycles in Northwest and Central European lacustrine sequences which are stratigraphically post-dating a glaciation, then can be compared on this level. Vegetation types, however, are only regionally comparable let alone forest species.

With regard to vegetational succession, trends are best compared to continuous palynological records such as those from Tenaghi Philippon, located in an intramontane basin in Greece, and from the maar lake sequences (Lac du Bouchet/Praclaux) in the Central Massif in France (*Fig. 4.6*). These sequences span several interglacial-glacial cycles and contain one or more geochronometric control points. Their palynological records reflect vegetational cycles of forested and non-forested periods. From these records, a chronological framework has been established for biostratigraphical comparison which has also been matched with the MIS to about 500 ka ago (Tzedakis *et al*. 1997, 2001). Matching also shows the shorter trends in climate change, reflected in the high cyclicity of forest vegetation climaxes. Amplitudes, however, show a lesser coherence. Both records are type sequences in their regions on the southern margins of the European continent. Nevertheless, they are regarded here as reference records on a European scale concerning trends in Middle Pleistocene zonal vegetational and climate change (*Fig. 4.6*). This may not only hold for warm stages but also for the cold stages. The prolonged periods of steppe vegetation distinguished in the Tenaghi Philippon pollen record, for example, may be well correlatable to the Central European loess accumulation cycles.

Terminology: lacustrine synthems are here informally named according to their type locality and, when relevant, the number of depositional cycles which can be distinguished: e.g. Reinsdorf I lake synthem. The lacustrine sequences are here informally named after the type locality, the lake type (lake origin) and/or depositional environment: e.g. Praclaux maar lake sequence as part of the Lac du Bouchet maar lake sequence group, Neumark-Nord glacial lake sequence, Bilshausen salt dissolution lake sequence.

[b] Other sequences from terrestrial (sub)environments

Locally distributed sequences from various depositional subenvironments, briefly discussed in *section 3.2.6*, are here informally named after their type locality to which their origin is added. Some examples of important markers in regional stratigraphies are:
- Volcanic deposits from the Eifel region: the Kärlich KAE-DT and KAE-BT tephra synthems,
- Secondary carbonates in fluvial terrace deposits in the Thuringian Basin: the Bilzingsleben travertine synthems.

4.3 Interregional correlation of the land-based Middle Pleistocene sequences

Continental and global correlation ultimately cannot be based on interpreted palaeoclimatic stages, whatever their boundaries, but on the multidisciplinary basic geological evidence of local records reflecting preserved depositional sequences bounded by unconformities and representing different scale and magnitude events.
This evidence has been dealt with as such in *section 3.5* where it has been divided into, and informally introduced as, sedimentary groups or ‘high-rank lithostratigraphical’ units which are characteristic for and within the natural geotectonic type regions of Northwest and Central Europe. According to the most widely distributed sediment types, they corroborate a two-fold subdivision into formerly glaciated areas and the extraglacial areas beyond, extending from northern France to Ukraine and Russia. This distinction is essential because the stratigraphy in these areas rests on different lithologies, tills and related glacial deposits versus loess and terrace gravels, and on different interpretative lithogenetic and climatostratigraphical criteria.

Without being complete, a compilation of both contemporary stratigraphies with regard to the Middle and Late Pleistocene data from Northwest and Central Europe is produced in *Figures 4.7* and *4.8* along W-E transects. They build supplementary frameworks in which the sedimentary sequences are arranged according to superposition, dating and interregional correlation of their major bounding unconformities. Since unconformities are very common in the Pleistocene terrestrial record, the use of the latter as a distinguishing criterion has been proposed in *section 2.6.1* under the pretext of creating a supplementary frame of objective, non-interpretive units without a genetic and causal meaning, similar to lithostratigraphical units. In the last edition of the International Stratigraphic Guide (Salvador (ed.) 1994) unconformity-bounded units, synthems, are recognised as formal components of stratigraphical correlation to which in many cases a (semi-)chronostratigraphical significance may be attributed. That is, although they are not equivalent to formal chronostratigraphical units, their containing depositional sequences c.q. their unconformable boundaries may coincide with particular time intervals during different scale events. Hence regional schemes are built of alternating depositional and non-depositional/erosional environments correlative at spatial scales.

The stratigraphical relationships between the genetically-related synthems building the interregional stratigraphical frames of *Figs. 4.7* and *4.8* are summarised and further discussed in the next sections by working down through the Middle Pleistocene succession. The sequences in both figures are arranged within the climatostratigraphical subdivision of Northwest Europe and plotted against the loess and pollen reference records in the Central European extraglacial areas. To avoid confusion and mixing of stratigraphical units of different types, the present existing local names of the including (litho)stratigraphical units are used in the two correlation schemes. An informal terminology for their interpretation as unconformity-bounded genetic sequences has been proposed in *section 4.2*, where nomenclature refers to type region, source area and locally known stratigraphical code.

4.3.1 Glacial stratigraphy of Northwest (and Central) Europe

As one can see from *Figure 4.7* the glacial sequences are spatially the most wide-spread units. They have been deposited at the end of three cold stages, as products of the Fennoscandian Elsterian, Saalian and Weichselian glaciations and of the British Anglian, Wolstonian and Devensian glaciations. Glacial sequences are immediately followed by marine sequences in the North Sea basin and by local lacustrine sequences onshore. The Middle Pleistocene alluvial plain and fluvial terrace sequences contemporary with, or intermediate between, wide-spread (peri-)glacial and marine units show responses to climatically-induced changes by adjustments of river modes, gradients and even courses.

[a] The glacial sequence within the Saalian Stage

The different regional subdivisions of the Saalian glacial sequence in Northwest Europe are, as an example of its complexity, discussed in more detail:

- In the northern Netherlands and western Lower Saxony, deposits including Holsteinian floras are overlain by a single till unit. This is attributed to the Drenthe Substage of the Saalian glaciation, which reached the lower Rhine basin and generated large push moraines.
- In eastern Lower Saxony and Schleswig-Holstein (Germany) three different post-Holsteinian, pre-Eemian till units are found representing three presumably separate glacial phases: a till unit equivalent to that in western Lower Saxony and the Netherlands, which is in northern Germany overlain by two further till units. The lowermost of these is defined as the Drenthe-2 till of the Middle Saalian Glaciation and the uppermost as the Warthe till of the Younger Saalian Glaciation (Meyer 1983, Ehlers 1991). In contrast, in Lower Saxony only the Younger Saalian till is regarded as ‘Warthe’, in Schleswig-Holstein and Hamburg the till units of the Middle and Younger Saalian glaciation (the Niendorf Till and the Fuhlbüttel Till) are attributed to the Warthe Substage. Ehlers (1991) has referred to much misunderstanding in German correlation due to the poor definition of stratigraphical units.
- In Denmark, three Saalian till units are distinguished (Houmark-Nielsen 1987), which are, from the base: the Trelde Naess Till, the Ashoved Till and the Lillebaelt Till. The former two tills were deposited by advances from Norway and from the northeast respectively, and are correlated with the Drenthe Substage. They are followed by a second advance reaching central Jylland which is correlated with the Warthe Substage.
- Extensive Middle Pleistocene glacial sequences can be observed in southeastern Germany as a consequence of the large-scale mining of lignite. In this region two main Saalian till units (gS1 and gS2) are distinguished, which at their southern distribution are subdivided into more till units representing recessional ice front oscillations (Eissmann 1975, 1990). Each glacial substage is subdivided into two phases of ice-(re)advance: the Zeitzer and Leipziger Phase in the Drenthe Substage and the Fläming/Schmiedeberg Phase and the Lausitzer Phase in the Warthe Substage.

The intensity of warming between the three principal ice-sheet advance phases of the Saalian glaciation s.s. (= Fennoscandian glacial sequence C in *Fig. 4.2*) has been a matter of debate. Although it has been suggested that the Drenthe and Warthe substages are separated by an ice-free interval in the area south of the Baltic (Mania 1992, based on the lake sequence of Neumark-Nord[7]), no lacustrine or marine temperate stage deposits from this interval have been found so far in Northwest Europe (Ehlers 1991, Eissmann 1991, Turner 2000). Polish and Russian evidence of a temperate stage (Pilica, Grabowka, Odintsovo), separating the Polish Odra and Warta glacial substages and the Russian Plain Dniepr and Moscow substages, may imply that these glacial synthems are not equivalent with the Drenthe and Warthe glacial synthems in Northwest Europe. Pollen evidence from intermediate sediments at Belchatow in Central Poland (Krisztowsky 1991) reveals only a *Betula-Pinus* forest phase which are both pollen producers of long-distance dispersal. They may have been incorporated in the fluvial sediments deposited during the short-termed ice-free interval. The Dniepr and the Moscow glacial synthems in the type regions on the Russian Platform possess different lithological properties and are intercalated by fluvial and, occasionally, lacustrine deposits. These have been attributed to the Odintsovo warm Stage, but its stratigraphical position has been revised and is now attributed an older age (Velichko and Faustova 1986). Thus, in the absence of equivocal evidence to the contrary, it is assumed that there was no warm climate event between the Saalian glacial sequence (*cf.* Turner 2000).

[b] The non-glacial sequences of the Saalian Stage

Is the Saalian a single, complex cold stage, or were some of the warming phases of temperate magnitude, implying that the Saalian cold Stage may include more than one interglacial-glacial cycles. There is only one indication of a glacial depositional cycle: the Liwiec glaciation in Poland succeeds the Holsteinian/Mazovian warm Stage and is assumed to be of post-Elsterian age (Lindner 1981, 1988). There is also ample evidence of temperate events post-dating the Holsteinian warm Stage but preceding the Saalian glaciation sensu stricto. Lacustrine and organic deposits intermediate of Holsteinian deposits and underlying Saalian till synthems

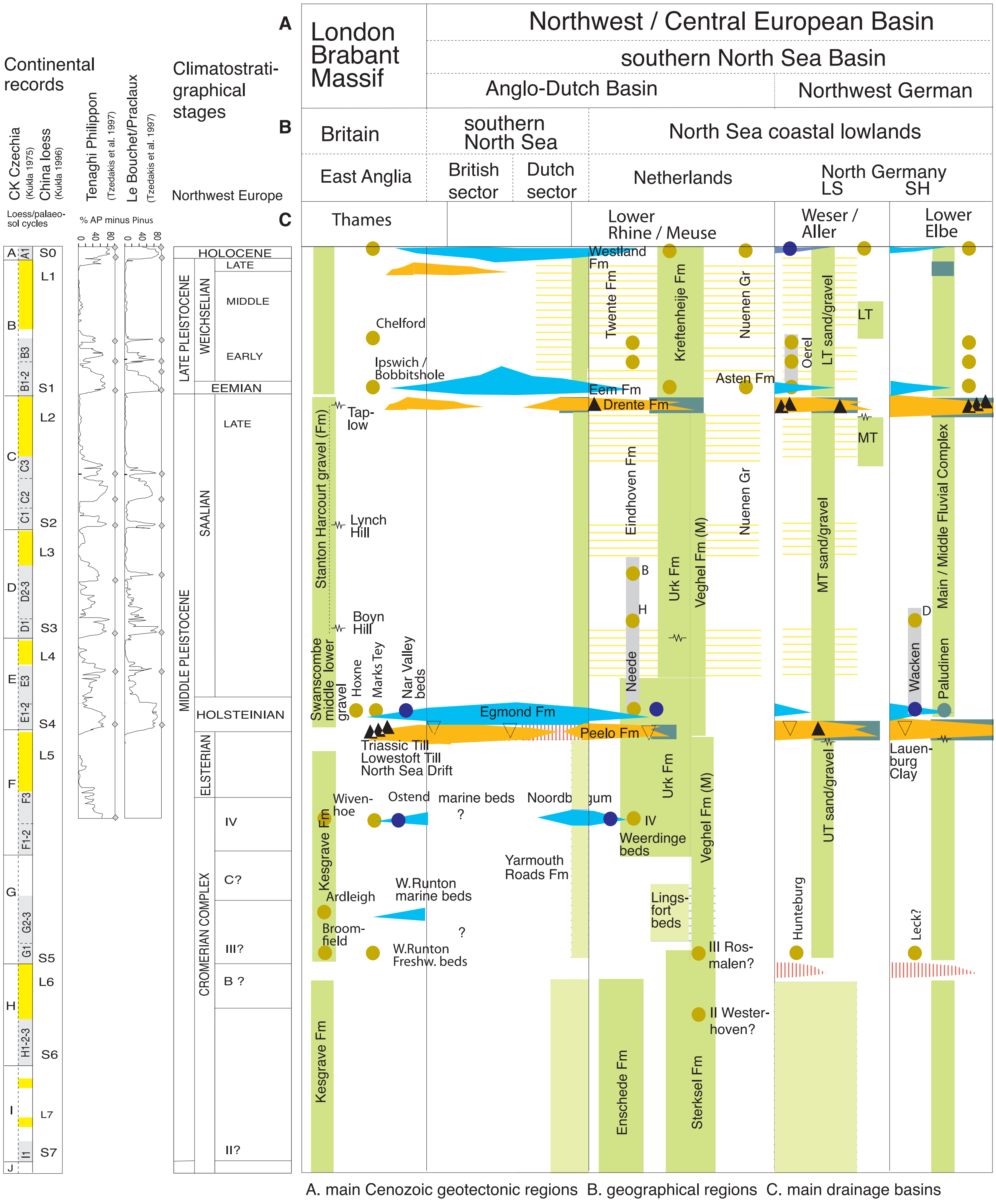
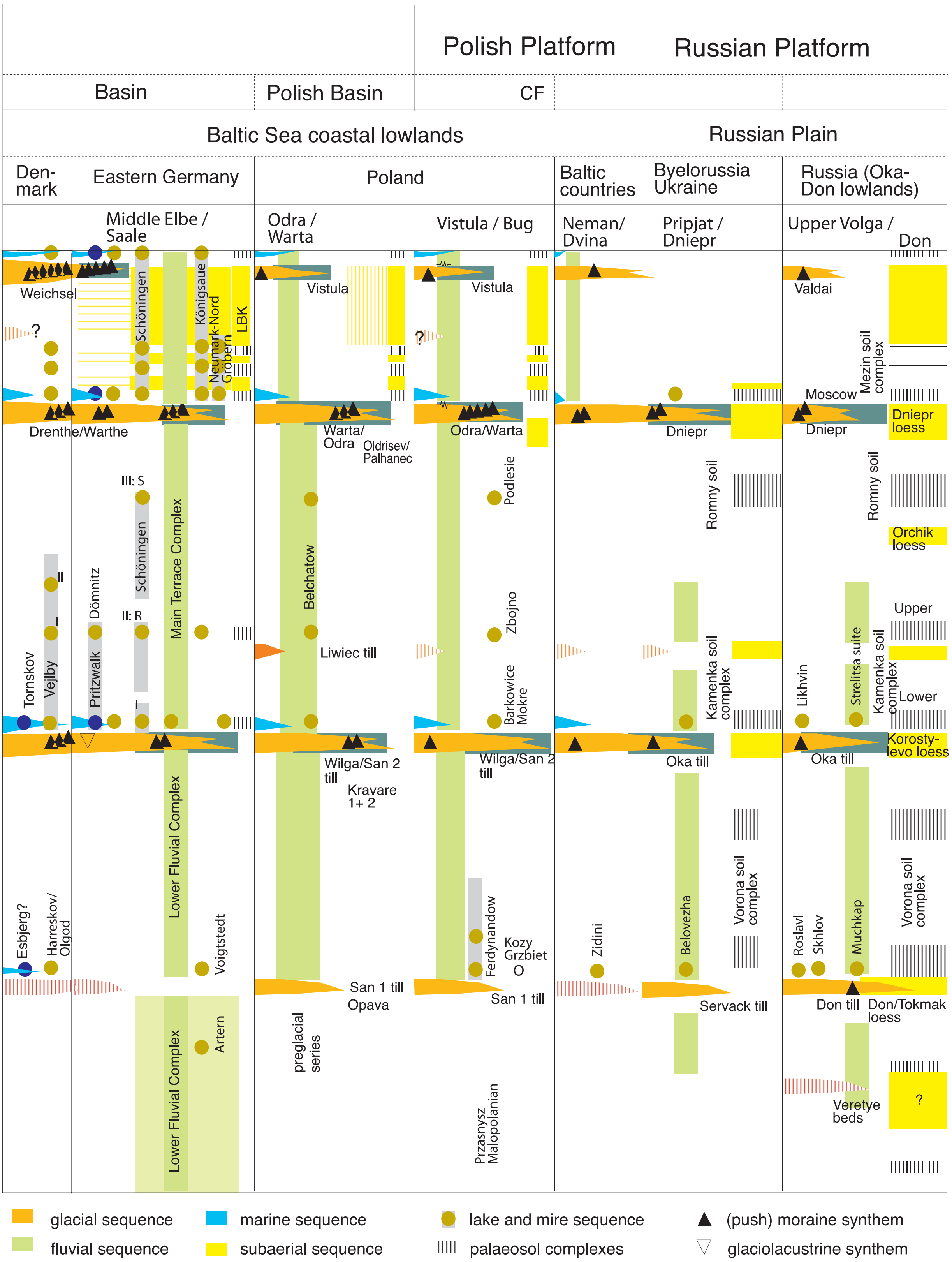


Figure 4.7 Middle and Late Pleistocene genetic sequence stratigraphy for the glaciated areas in Northwest and Central Europe.


Polish Platform
Russian Platform
Basin
Polish Basin
CF
Baltic Sea coastal lowlands
Russian Plain
Denmark
Eastern Germany
Poland
Baltic countries
Byelorussia Ukraine
Russia (Oka-Don lowlands)
Middle Elbe / Saale
Odra / Warta
Vistula / Bug
Neman/ Dvina
Pripjat / Dniepr
Upper Volga / Don
Weichsel
?
Schöningen
Königsaue
Neumark-Nord
Gröbern
LBK
Vistula
Vistula
?
Valdai
Mezin soil complex
Moscow
Drenthe/Warthe
Warta/ Odra
Oldrisev/ Palhanec
Odra/Warta
Dniepr
Dniepr
Dniepr loess
III: S
Podlesie
Romny soil
Romny soil
Schöningen
Main Terrace Complex
Belchatow
Orchik loess
II
Dömnitz
Zbojno
Upper
II: R
I
Liwiec till
Kamenka soil complex
Strelitsa suite
Kamenka soil complex
Tornskov
Vejlby
Pritzwalk
I
Barkowice Mokre
Likhvin
Lower
Korostylevo loess
Wilga/San 2 till
Kravare 1+ 2
Wilga/San 2 till
Oka till
Oka till
Lower Fluvial Complex
Vorona soil complex
Vorona soil complex
Esbjerg?
Harreskov/ Olgod
Voigtstedt
Ferdynandow
Kozy Grzbiet
O
Zidini
Belovezha
Roslavl
Skhlov
Muchkap
San 1 till
Opava
San 1 till
Servack till
Don till
Don/Tokmak loess
Lower Fluvial Complex
Artern
preglacial series
Przasnysz Malopolanian
Veretye beds
?
glacial sequence
fluvial sequence
marine sequence
subaerial sequence
lake and mire sequence
palaeosol complexes
(push) moraine synthem
glaciolacustrine synthem

have been recognised from several localities in Northwest and Central Europe. They represent the Wacken Substage in Schleswig-Holstein (Menke 1968), the Dömnitz Substage in eastern Germany (Erd 1970) and the Vejlby I organic intercalations in Denmark (Anderson 1965). These warm climatic events record a second forest vegetation cycle, lacking *Pterocarya*, that has been preserved before the glacial lakes became silted up. Two *Betula-Pinus* forest phases, termed Hoogeveen and Bantega, are found in Saalian sands underlying till of the Drente Formation in the northern Netherlands (Zagwijn 1973). The Hoogeveen Interstadial in particular shows evidence of rather warm climatic conditions. Although stratigraphical control is lacking, this event is tentatively correlated with the above-mentioned forest periods and with the Schöningen warm event pollen assemblage zone (PAZ) in Lower Saxony (Urban *et al.* 1988).

Lacustrine and organic deposits containing quite different pollen successions than the Dömnitz/Hoogeveen/Schöningen warm periods are found in Poland (Lindner & Brykczynska 1980) and in Lower Saxony (Urban 1993), representing the Zbòjno and Reinsdorf warm periods respectively. Although their lithostratigraphical position is not clear as yet, they suggest the occurrence of another warm period post-dating the Holsteinian Stage. The lacustrine and organic layers in the Schöningen mine, intercalated between Elsterian and Saalian glacial sequences, are of interest for the late Middle Pleistocene stratigraphy and are further discussed in *section 5.4*.

[c] The Holsteinian temperate Stage

Marine and limnic deposits assigned to the Holsteinian Stage are found throughout Northwest Europe in a stratigraphical position overlying the Elsterian glacial sequence. They are regarded to represent the warm temperate period following the Elsterian glaciation accompanied by high sea-levels in the North Sea area.

The sequences infilling lake basins developed on the preceding glacial deposits contain typical pollen spectra, regionally referred to as Holsteinian, Hoxnian, Mazovian and Likhvin (warm stage) type pollen assemblage zones. They show a rather uniform forest vegetation development dominated by conifers and deciduous trees. Pollen spectra contain *Pterocarya* in a late-temperate phase, as well as the presence of the water fern *Azolla filiculoides*. Contemporary fluvial sequences are characterised by the abundant presence of the molluscs *Viviparus diliviana* and *Corbicula fluminalis*.

[d] The Elsterian cold Stage

Glacial sequences ascribed to the Elsterian Stage are found underlying Holsteinian Stage beds at many localities. Apparently Elsterian tills are found in Denmark (three till units: Sønder Vissing, Pålsgard and Snoghøj) and in northern Germany (two till units: Elster 1 and 2). In eastern England, two Anglian till units occur: the North Sea Drift and Lowestoft Till Formations. In Poland and Russia, the Elsterian glacial sequence is more complex. The Holsteinian/Mazovian warm-stage deposits in Poland are underlain by two till synthems of the San glaciation. These are, however, separated by the lacustrine sequence of the Ferdynandov warm Stage, implying that only the upper San 2 glacial sequence equates the Elsterian cold Stage. In Russia the Okian glacial sequence is clearly the equivalent of the Elsterian.

[e] The'Cromerian Complex' Stage

Primary glacial deposits older than the Elsterian and Anglian glaciations cannot be demonstrated in the Northwest European lowlands (Ehlers *et al.* 1983, Eissmann 1990). There are, however, some indications of a pre-Elsterian ice-sheet advance reported from the northern Netherlands (Scandinavian erratic material in the Weerdinge Beds of the fluvial Urk Formation, Zandstra 1971), from Denmark (diamicton deposits at the base of the lake sequence of Harreskov and Ølgod, Andersen 1965) and from Lower Saxony (diamicton material in a karst lake in the northern Harz foreland, Grüger 1967). This is in contrast to eastern Europe where glacial sequences of at least one and probably three pre-Elsterian glaciations have been recorded (in Ehlers *et al.* 1995). Since the Donian glacial sequence in central Russia is normally magnetised (Krasnenkov *et al.* 1997), it is clear that this part of Europe was affected by at least one major Fennoscandian glacial event, with a more easterly accumulation centre, during the early Middle Pleistocene. It also seems likely that the San 1 tills of Poland and the Servack and Narev tills of Byelorussia and western Russia were produced by pre-Elsterian glaciations (Velichko and Faustova 1986). Several organic deposits are found intermediate of these early Middle Pleistocene till units. In Russia, the Okian and Donian glacial sequences are separated by the bi-optimal Roslavi/Muchkap warm-stage deposits which is comparable with the Ferdynandovian warm-stage deposits in Poland.

Because of the fragmentary nature of the sequences and in the absence of clear stratigraphical control, a more complicated picture emerges in Northwest Europe. Unfortunately, most local sequences that are stratigraphically situated below the Fennoscandian or British glacial sequences and that have been informally labelled as ‘Cromerian’, only have biostratigraphical control. Marine intercalations at the North Sea basin margins are found at Noordbergum in the Netherlands and at Ostend and West Runton in East Anglia. The latter two localities are part of the (organic) fine-grained fluvial and estuarine sequences of the Cromer Forest-bed Formation (Reid 1882, West 1980) exposed in many coastal sections. Recently, at least 6 warm-stage events of early Middle Peistocene age have been recognised in this pre-Anglian sediment complex on the basis of vertebrate and malacological evidence (Preece 2001). In the Netherlands 4 temperate substages have been identified from warm-stage fluvial sequences, mainly from palynological evidence. Three of them, Interglacial II (Westerhoven), Interglacial III (Rosmalen) and Interglacial IV (Noordbergum), are of early Middle Pleistocene age (Zagwijn *et al.* 1971). The British and Dutch sequences, however, are difficult to correlate. The distinction between local warm-stage sequences containing *Mimomys savini*, e.g. at West Runton and Voigtstedt, and those containing *Arvicola terrestris cantiana*, e.g. at Noordbergum and Ostend, is one of the most important biostratigraphical boundaries in the early Middle Pleistocene. The West Runton Freshwater Bed, the type unit of the Cromerian Stage s.s. (West 1980), contains Biharian mammalian faunas together with *Mimomys savini*, (in Turner 1996). The estuarine sediments at West Runton occur immediately above these organic warm-stage sediments. The first occurrence of *Arvicola* in warm-stage deposits is contemporary with *Elephas (Palaeoloxodon) antiquus* and *Hippopotamus amphibius* (Von Koenigswald and Van Kolfschoten 1996). The stratigraphical position of the *Mimomys/Arvicola* boundary in Russia is just above the Muchkapian Stage deposits overlying the Donian glacial sequence (Alekseev 1996). In the Middle Rhine area it is contemporary with the first volcanic activity in the East Eifel mountains dated at about 600 ka.

4.3.2 Fluvial terrace and loess stratigraphy of Central Europe

[a] Loess stratigraphy

The loess units in *Figure 4.3* and *Figure 4.8* in the extraglacial upland areas are generally located in river valleys and tectonic basins. They occur as spatially separated sequences within their type regions overlying river terrace deposits. Only in eastern Europe are loess sequences traceable over large areas. Next to primary loess, the sequences in many type areas include loess derivates and slope wash deposits. On a temporal scale the different loess units are separated by warm-climate palaeosol complexes and bounded by erosional unconformities.

Loess/palaeosol sequences are associated with global-scale glacial-interglacial climatic cycles. They are best documented in the subaerial loess/palaeosol key sections of Eurasia of which the China loess record (Kukla 1987) is shown as a reference. They have their counterparts in the terrace sequences in the uplands of Central and Northwest Europe. The most complete regional loess terrace stratigraphies are those of Červený Kopec (eastern Alpine Foreland), Kärlich and Ariendorf (Middle Rhine), Achenheim (Upper Rhine Graben) and St. Pierre-les-Elbeufs (Paris Basin).

Interregional correlations are relative and tentative. The nature and stratigraphical position of the loess/palaeosol sequences, and their preservation, is closely related to the regional river terrace and tectonic histories. Based on their combined stratigraphies, correlations then rely on the length of the record, biostratigraphical evidence and independent age control such as tephrochronology in the Middle Rhine type area. Also the palaeosol complexes are not that distinctive to allow interregional correlations without other evidence, with the exception of the pronounced brown forest soil types (PKVII) from different regions in between Central European loess cycles H and F.

Several late Middle Pleistocene loess sequences reveal three cold periglacial desert periods separated by soil formation. The loess cycle C in Central Europe is associated with the Fennoscandian glaciation cycle C in the Saalian Stage on the basis of its stratigraphical position below the soil complex of B and its distribution on top of terrace CK2. This aeolian unit is equivalent to the so-called Dniepr loess on the Russian Plain. The latter contains no palaeosols of interglacial type (Velichko 1990) and lies, together with its glacial equivalent in the north, the Dniepr Till, immediately upon the Romny palaeosol complex. Additional extraglacial evidence for two warm episodes following the Holsteinian Stage comes from palaeosols found in northern France, Slovakia and the Russian Plain. The loess cycle F in Central Europe is equated with the Elsterian/Okian glacial sequences. Their stratigraphical relationship is based on multidisciplinary evidence from different sedimentary environments and key sections which is comprehensively discussed in *chapters 5* and *6*. Older loess/palaeosol records with stratigraphical control are found in the Middle Rhine Neuwied basin and type areas in eastern Europe. At Mahlis in eastern Germany a loess sequence is found underlying Elsterian tills (Wiegank 1979). Primary loess deposits are missing in cycle G, as is also indicated in the Chinese reference record, while the soil groups in this interglacial-glacial cycle are more strongly weathered (Kukla 1977). Finally, the Donian loess and glacial sequences in central Russia are correlated to the loess sequence of cycle H in Central Europe.

[b] Fluvial terrace stratigraphy

The loess/palaeosol sequences in the Central European upland type areas are superimposed on fluvial terrace sequences. In an interregional context, it is the succession of aggradation and downcutting of the larger river systems that forms an important key in confining the stratigraphy of the extraglacial areas and in connecting glaciated and non-glaciated type regions. Correlation of the fragmentary fluvial terrace sequences, however, is not always straightforward, even within one drainage basin.

The Middle Pleistocene alluvial plain and terrace sequences in the lower sections of rivers draining northward into the glaciated areas, like the Elbe, Weser and Rhine are subdivided into upper, middle and lower terrace complexes. They are separated by the Elsterian and the Saalian glacial sequences (*Fig. 4.7*). The Saalian glaciation limit in the lower Rhine Basin affected the course and terrace sequence of the contemporary river. Between the Holsteinian and the Eemian Stages, two cold phases are represented by contemporaneous terraces (*Middle Terrace IIIb* and *Middle Terrace IV*; Brunnacker 1986). Klostermann (1992) distinguishes three terrace sequences within the Saalian Stage (*Lower Middle Terraces 2, 3* and *4*).

The terrace sediment bodies in the upland areas, separated by lateral unconformities, also are grouped into upper, middle and lower terrace complexes but on morphostratigraphical grounds. They are distinguished by clear changes in the basal erosion levels and comprise several coarse-grained lithofacies units associated with cold climate aggradation (*section 4.2.2*).

The erosional break from the middle terrace to the lower terrace complexes in the North German type areas coincides with the break in Central European loess cycle C from terrace *CK2* to *CK1* and the transition in the northern Alpine Foreland from the Hochterrassen to the Niederterrassen within the Rissian-Würmian Complex.

The base of the upper terrace complexes, predating the first (Elsterian) glacial sequence in the Elbe area ('*Frühelsterterrasse*': lacking erratic glacial material), features the deepest incision phase in the type area. A similar extremely incised valley is present in the Lower Rhine Embayment underlying the base of the *Middle Terrace IIIa* sediments or the '*Rinnenschotter*' (*section 5.3*). The heavy-mineral composition of the sand and gravel filling of the latter is dominated by pyroxenes, of which the first occurrence is dated about 500-450 ka, as are the alluvial sediments of the downstream AD/NS Urk I alluvial sequence group which are unconformably overlain by glacial sediments of the Elsterian glaciation. This striking erosional unconformity prior to the Elsterian glaciation is also found in terrace sediment systems of the middle and upper sections of the Rhine, Elbe and Danube rivers, beyond the glaciated areas. It corresponds with the break from *CK3* to *CK2* in the upper Danube Morava sub-basin (cycle F). Another conspicuous, anomalous morphological variation in the erosion base levels of the above-mentioned river systems, coinciding with the change from the *CK4* terrace to the *CK3* terrace during cycle H, is discussed in *section 4.4.3*.

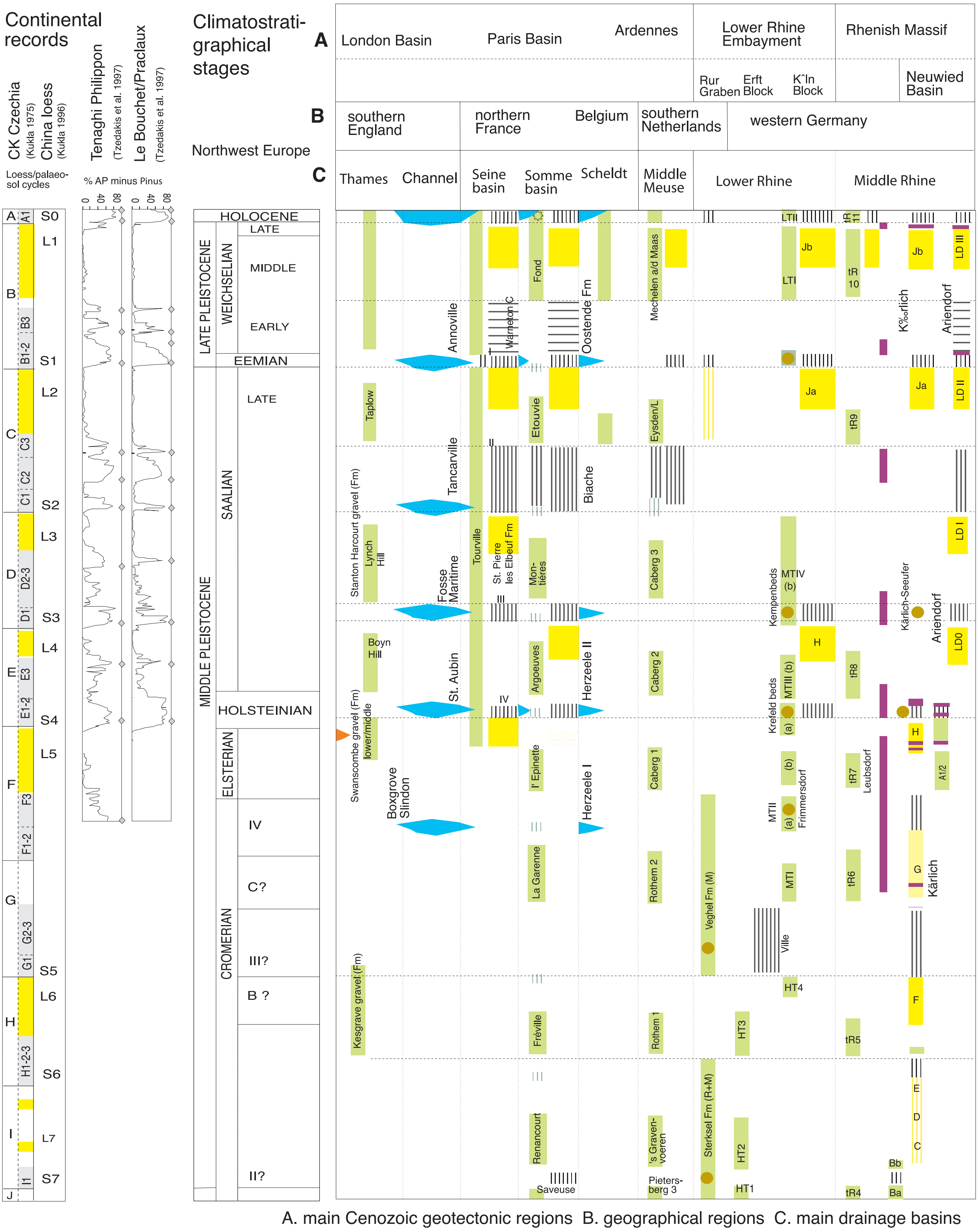
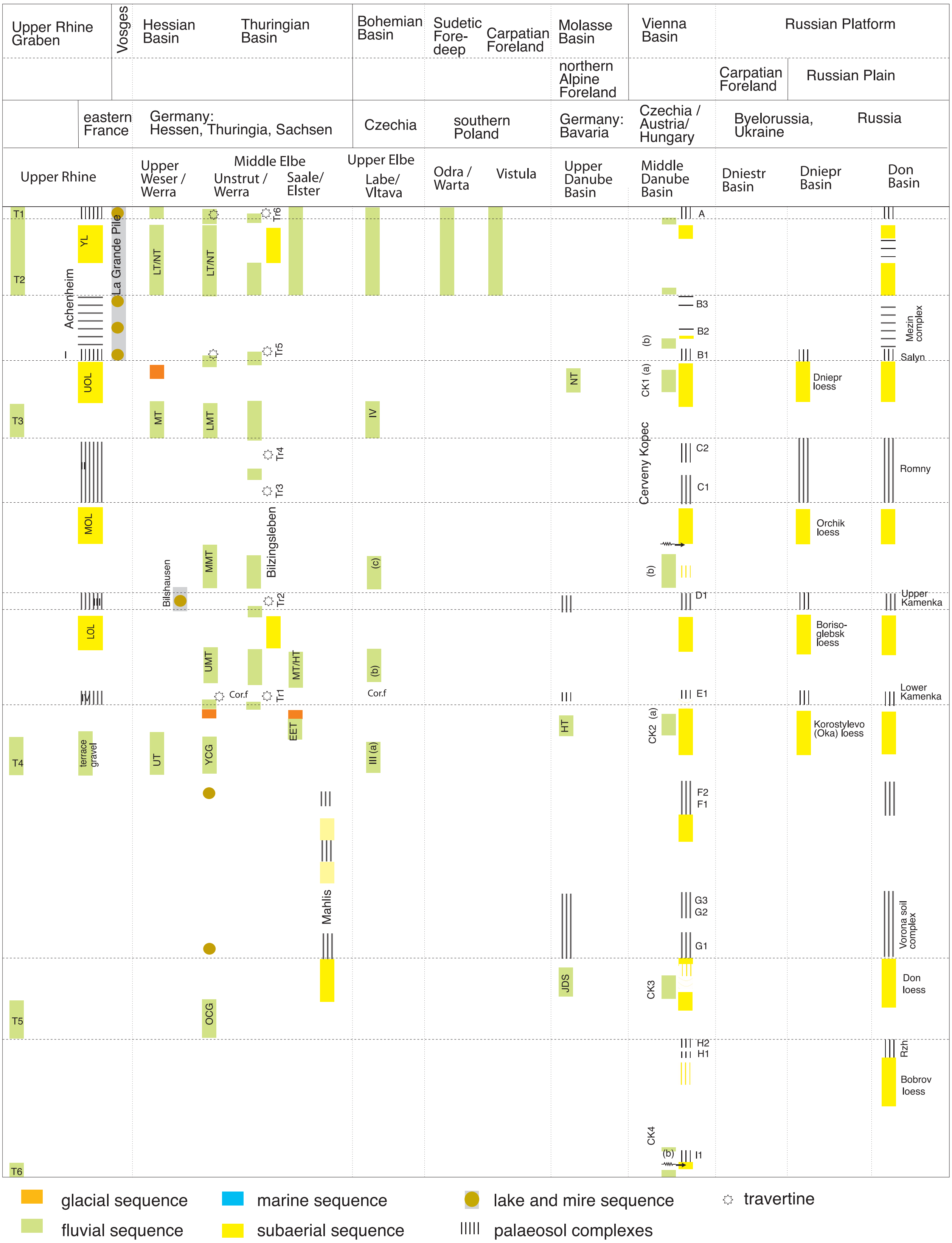


Figure 4.8 Middle and Late Pleistocene genetic sequence stratigraphy for the non-glaciated areas in Northwest and Central Europe.



🟧 glacial sequence
🟩 fluvial sequence
🟦 marine sequence
🟨 subaerial sequence
● lake and mire sequence
||||| palaeosol complexes
☼ travertine

4.4 Compilation of an event-stratigraphical framework for the Middle Pleistocene terrestrial record of Northwest and Central Europe

4.4.1 Interpretation of the palaeoclimatic event markers

Based on the unconformity-bounded genetic stratigraphical successions from the different type regions proposed here, a final interpretative procedure includes the reconstruction of an event stratigraphical framework. Supplementary procedures of interpreting and compiling a set of criteria for large-scale correlations has been introduced and discussed in *section 2.5.1*. Genetic sequences in the type regions are here classified and termed according to depositional environment, source area of the sediments and stratigraphical relationships. Each regional stratigraphical succession of environments contains multidisciplinary information on climatic and tectonic control at different spatial and time scales. This recognition is essential in the interregional reconstruction and chronological correlation of Middle Pleistocene environmental, climatic and tectonic event histories from the type regions and subsequently for global matching (*section 2.5.2*).

The followed procedure in fact is similar to the conventional procedure of building regional stratigraphical successions of interpreted climatic stages. However, uniformly-defined genetic sequence units are used as a basis and relevant information from the contemporary and intermediate non-glacial environments has been adapted for (short-term) local and regional effects before large-scale correlations are made. The overall subdivision in this approach is not influenced by 'counting down from the top' of wide-spread globally significant stages and locally inferred and mostly temperature-related parameters, i.e. cold and warm substages, in the succession at equal scale level. Instead, subdivision of significant sedimentary units and events intermediate of the fixed glacial or periglacial aeolian sequences is achieved by 'counting upward from the base' of an MIS-fixed sequence to the basal unconformity of the next fixed sequence. This procedure implies the occurrence of considerable hiatuses between the large-scale event-stratigraphical units. Since preservation potential decreases with time from the basal MIS-fixed unit, the largest hiatuses can be expected, for example, after levelling of glacial relief and below the next major erosional unconformity which generally has involved removal of the upper part of the surface.

Events of global magnitude, which are responsible for wide-spread cyclicity in the sedimentary record, are associated with tectonics, palaeogeomagnetic reversals, climatic change and eustatic sea-level fluctuations. These events may serve as a global template for chronostratigraphical correlation, although operating at different scales. Geological and biological/ecological events identified in this thesis, as explained in *section 2.6.3*, not only refer to short-term catastrophic phenomena but particularly include climate-driven events, tectonics or sea-level changes with 5*th* and 4th order frequencies of 0.001 - 0.1 Ma.

Glacial and periglacial aeolian (loess) sequences are markers with interregional event-stratigraphical significance, exclusively associated to mid-latitude glaciations and extreme cold deserts. The preserved sequences in most type regions, however, are represented by incomplete stratigraphical cycles. Cycle boundaries are spatially represented by wide-spread maximum distribution limits and temporally by basal unconformities in vertical geological sections. Nevertheless, the sequences can readily be related to events indicative for large-scale zonal and global climate change, such as glaciations, periglacial deserts and sea-level fluctuations for which ultimately the marine isotope stratigraphy can be used as a reference for timing and, to a lesser degree, patterning. They are summarised in *Figure 4.9* for Northwest and Central Europe on a relative time scale, together with bio- and chronological marker events.

The dynamic events have also drastically remodelled land surfaces, are responsible for major erosional unconformities and have created new depositional environments, for example, the lakes infilled during subsequent deglaciation. The number of preserved regional glacial and periglacial aeolian sedimentary cycles, initially determined by geographical position and ice-sheet dynamics/intensity, is eventually fixed by syn- and post-depositional features resulting from (repeated) erosion, burial, deformation and resedimentation.

The glacial and periglacial sequences left behind in renewed palaeogeographical situations have also preconditioned further palaeoenvironmental development in many type regions. The initially unvegetated post-glacial landscapes have subsequently been levelled by non-glacial environments or have otherwise been subjected to soil formation. These local and regional sequences and unconformities from fluvial, lacustrine, subaerial and other environments, coinciding and alternating with the wide-spread sequences, are embedded in the large-scale stratigraphical framework. Several of the small-scale sequences show detailed palaeoenvironmental and -climatic information, with a high time-resolution, which is of great importance in spatial analyses. Unfortunately, they also reflect bio-geographical and geotectonic variability which have not always been consistently assessed in large-scale correlation of climatically-induced sedimentary cycles in mid-latitude Europe.

Searching boundary levels for these terrestrial climate-driven signals in the marine isotope stratigraphy may provide a supplementary basis for the chronostratigraphical subdivision of the terrestrial Quaternary sequence. Although the boundaries of the regional depositional sequences are time-transgressive, corresponding geological events and climatic stages can be fixed to particular time intervals in the ocean record. Nevertheless, conclusions drawn on the regional response to global climatic change should be confirmed by independent evidence and include corrections for among others neotectonics co-controlling accomodation space, sediment supply and base levels.

In conclusion, the stratigraphical table in *Figure 4.9* shows a sequence of events for Northwest and Central Europe which is compatible with the sequence of palaeoenvironments revealed by:

- Lithostratigraphy, from both the glacial and extraglacial areas in Europe (and Eurasia),
- The limited amount of dating evidence available,
- The continuous pollen records of the French Maar lakes and Tenaghi Philippon as well as a number of fixed short-term pollen records from glacial lake sequences,
- Faunal evidence from local sequences, and,
- Independent evidence from major unconformities, such as fluvial terrace surfaces and soil complexes.

The nomenclature of events refers to the geological process and the regional name or type locality for which the events are significant, e.g. Fennoscandian glacial cycle C, Praclaux maximum forest assemblage.

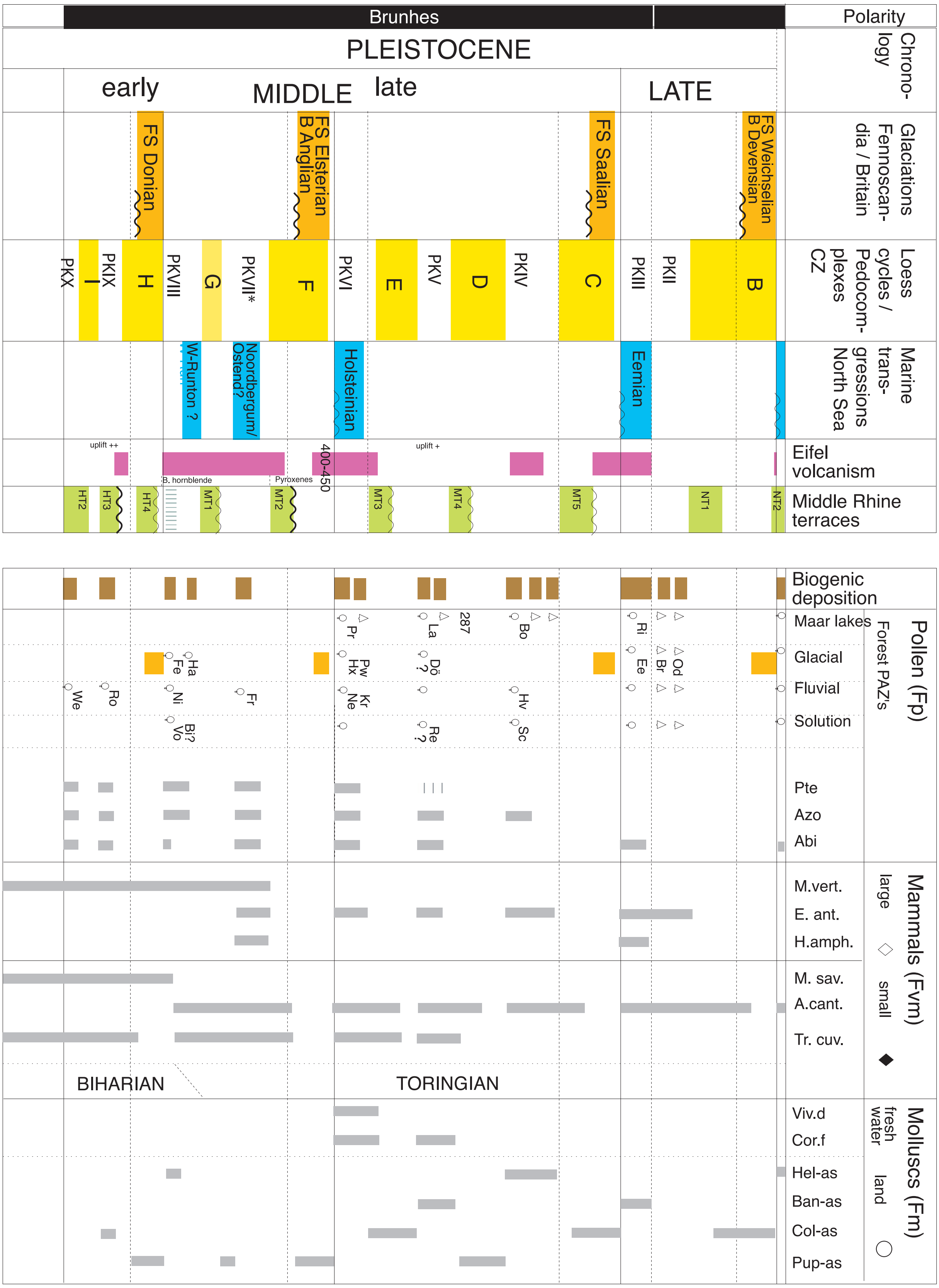


Figure 4.9 (Terrestrial) event stratigraphical subdivision and bio-indicators of the Middle and Late Pleistocene for Northwest and Central Europe.

4.4.2 Relevant chrono- and biostratigraphical markers of interregional significance

Markers and climate-indicators preserved in the sedimentary records of the type regions yield predominantly relative time control of the Middle Pleistocene climate and tectonic histories. This independent dating evidence is summarised below and shown in *Figure 4.9*. They are of great help in constraining and refining the chronostratigraphical positions of both large- and small- scale depositional sequences and related events. Markers of assumed supraregional significance from different environments applicable within the type regions of Northwest and Central Europe are:

1 Fossil faunal assemblages:

- Small mammals: the *Mimomys savini* / *Arvicola terrestris cantiana* boundary in fluvial, lacustrine and subaerial sequences which postdates the Donian glaciation (Fennoscandian glacial cycle H) and its subsequent temperate stage and which is contemporaneous with the first occurrence of East Eifel volcanics dated at about 600 ka. The evolutionary level change of *Arvicola terrestris cantiana* Ssp. A to B, on the basis of SDQ-values, occurring in between the Elsterian glaciation (glacial cycle F) and the Saalian glaciation (glacial cycle C). LAD[8] of *Trogonterium cuvieri* in lacustrine and fluvial environments which is post-dating the Elsterian glaciation.
- Large mammals: *Elephas (Palaeoloxodon) antiquus* which is found in fluvial and lacustrine environments of warm stages post-dating the Donian glaciation. LAD of *Megaloceros dawkinsi* occurring in sediments of cold stages preceding the Elsterian glaciation; *Coelodonta antiquitatis* and *Mammuthus primigenius* which have their FAD[9] in the cold stage post-dating the Elsterian glaciation;
- Mollusca: land mollusc assemblages from loess/palaeosol sequences indicating to the climate intensity, both for cold stages (*Columella* and *Pupilla* faunas) and warm stages (*Banatica* faunas). Freshwater molluscan assemblages from fluvial sequences: *Corbicula fluminalis* and *Viviparus diluviana* occurring in the first two warm stages intermediate of the Elsterian glaciation and the Saalian glaciation.

2 Fossil pollen assemblages (from late-temperate vegetation zones):

- *Pterocarya* of which the LAD is in lake records immediately following the Elsterian glaciation in Northwest Europe and the Praclaux forest vegetation optimum in the Central Massif, dated older than 300 ka.
- LAD of the water fern *Azolla filiculoides* in lake records predating the Saalian glaciation.
- Presence of *Abies* in lowland lake records indicative of warm stages with oceanic influence.

3 Geochronological age estimates and dates:

- The Brunhes/Matuyama geomagnetic reversal from suitable volcanic rocks and fine-grained lithofacies assemblages as a marker for the base of the Middle Pleistocene.
- K/Ar- and Ar/Ar-dates from regional volcanic marker beds as known from six eruptive phases in the East-Eifel region, providing a tephrochronological control on the Middle Rhine fluvial terrace and loess sequences. Another example are the tephra strata in the Central Massif, confining among others the Lac du Bouchet/Praclaux pollen record (De Beaulieu and Reille 1995).
- TL/OSL dates from (Late Pleistocene) loess deposits.
- U-series age estimates from secondary carbonates, such as that from Bilzingleben (although the dates appear to be less suitable beyond 100 ka).
- Relative dates from amino-acid ratios of molluscan shells from marine and fluvial sequences. The former are of some importance in distinguishing chronostratigraphical positions for the late Middle Pleistocene.

4 Fossil soil complexes representing unconformities formed under extreme warm climate conditions. For example, the pronounced red soils (PKVII) occurring in cycle F from Červený Kopec.

5 Regional geotectonic events (*next section*).

4.4.3 Regional geotectonic variability

Another important aspect providing independent evidence to confine the climatically-induced sedimentary cycles, concerns the syn- and post-sedimentary neotectonic control on the distribution and preservation of local and regional sequences, particularly those from fluvial, marine and lacustrine environments. While playing a role at both regional scale (vertical movements in basins, grabens and mountain areas) and local scale (faults, salt tectonics, landslides, karst), tectonics whether it results or not from glacio-isostasy, should be taken into account before comparing sequences for global-scale climatic change.

Neotectonics operate at different scales independently of climatic change. Kukla and Cílek (1996) in their megacycle-concept, 'a record of climate and tectonics', suggest that accelerated tectonic movements in the Alpine and Hercynian mountain ranges of Europe could be coeval with exceptionally well developed loess units and terrace formation. They also suggest, *cf.* Raymo and Ruddiman (1992), a cause-and-effect relationship between phases of accelerated mountain uplift, basin submergence and/or rearrangements of the ocean floor, bringing about deflected atmospheric circulation, and the occurrence of the most extensive glaciations. Moreover, Zubakov and Borzenkova (1990) suggest that there might be a relationship between increased tectonic activity and the orbital cyclicity frequencies of 400 ka and 1.2 Ma.

Independent evidence of major neotectonic phases comes from both the glaciated lowland areas and the extraglacial terrace sequence stratigraphies in the tectonically active upland regions of Northwest and Central Europe. Here three major erosional steps separate the terrace sediment complexes north of the Alps within the Brunhes Chron. They comprise the Upper, Middle and Lower Terrace complexes, also dealt with in *section 4.3.2*. Kukla and Çilek (1996) associate them with regional tectonic re-arrangements or phases of uplift, relative to the basins, as a response to extreme glaciations. Although the latter two erosional anomalies may be related to glacio-isostatic effects of the Saalian and Elsterian glaciations, the erosional morpho-tectonic change in the early Middle Pleistocene, seems to be related to an independent tectonic event of accelerated uplift, dated roughly between 1.1 - 0.7 Ma. It separates the terrace accumulations of:

- The *Deckenschotter Complex* (Günzian/Haslachian/Mindelian Complex) from the *Hochterrassen* (Rissian/Würmian Complex) in the northern Alpine Foreland (nAF),
- The *CK4 terrace* from *CK3 terrace* in the loess terrace sequence of Červený Kopec in the eastern Alpine Foreland, and
- The *Hauptterrassen Complex* from the *Mittelterrassen Complex* in the Middle and Lower Rhine type areas.

Correlation is complicated because of regional differences. The dating of this tectonic erosional unconformity is based on:

- The presence of the Brunhes/Matuyama boundary in the nAF *Deckenschotter Complex* as well as in the Middle Rhine *Hauptterrassen Complex* which makes an early Middle Pleistocene age plausible.

- The strongly weathered surfaces of both above-mentioned terrace complexes which took place during CK loess cycle F (MIS 15-12), implying that the erosional unconformity must at a maximum date from MIS 16. This would also imply that the Alpine Mindelian glaciation is not equivalent to the Elsterian glaciation of northern Europe, but to the previous Donian glaciation of which only little evidence is found in Northwest Europe.

The relationships between tectonics, climate, eustacy and basin development, controlling the balance between sediment supply and accommodation, in the Pleistocene is a sequence-stratigraphical problem that needs to be further analysed.

[1] *High relief areas have elevations generally above 1000 m above sea-level (a.s.l); moderate relief areas (uplands) have elevations generally between 200 and 1000 m a.s.l.; low relief areas have elevations generally below 200 m a.s.l.*

[2] *And partly still continuing.*

[3] *e.g. craters and calderas.*

[4] *Such as kettle holes, pingo ruines and oxbox lakes.*

[5] *Next to local glaciation centres such as the Vosges, the Black Forest mountains, the Harz and the Carpathians.*

[6] *Basin subsidence rates and isisotatic uplift rates in surrounding areas.*

[7] *It is true that Mania (1992) found a vegetation phase prior to the Eemian vegetational optimum at the lake sequence of Neumark-Nord but they do not reflect a forest pollen stage.*

[8] *LAD: last appearance datum.*

[9] *FAD: first appearance datum.*

Chapter 5

KEY STRATIGRAPHICAL SEQUENCES FOR THE MIDDLE PLEISTOCENE IN NORTHWEST AND CENTRAL EUROPE: TWO CASE STUDIES

5.1 Introduction

Several local key sections in different geotectonic type areas have been reviewed during this study to which in different steps the regional criteria for a genetic sequence - and event-stratigraphical subdivision are applied to contribute to a continent-wide chronostratigraphical framework. The case studies are examples of analyses of sedimentary sequences from available multidisciplinary evidence compiled from cores and geological sections which have been published in the open literature. Examination of this evidence emphasises that the interpretations differ and have changed in time with increasing evidence availability, new insights and dating techniques. Therefore, careful study of the basic objective evidence is essential and includes one of the main tasks in compiling local data before regional and continent-wide extrapolations can be made. One of the best ways to inspect local situations, i.e. by means of personal checks in the field, were undertaken on several occasions during this study. Furthermore, there were opportunities to visit several other sections during international field trips and excursions and have personal communication with local field workers.

Two key sequences for the Middle Pleistocene stratigraphy of Northwest Europe were investigated during two-week field work observations, the results of which will be discussed and synthesised further below:

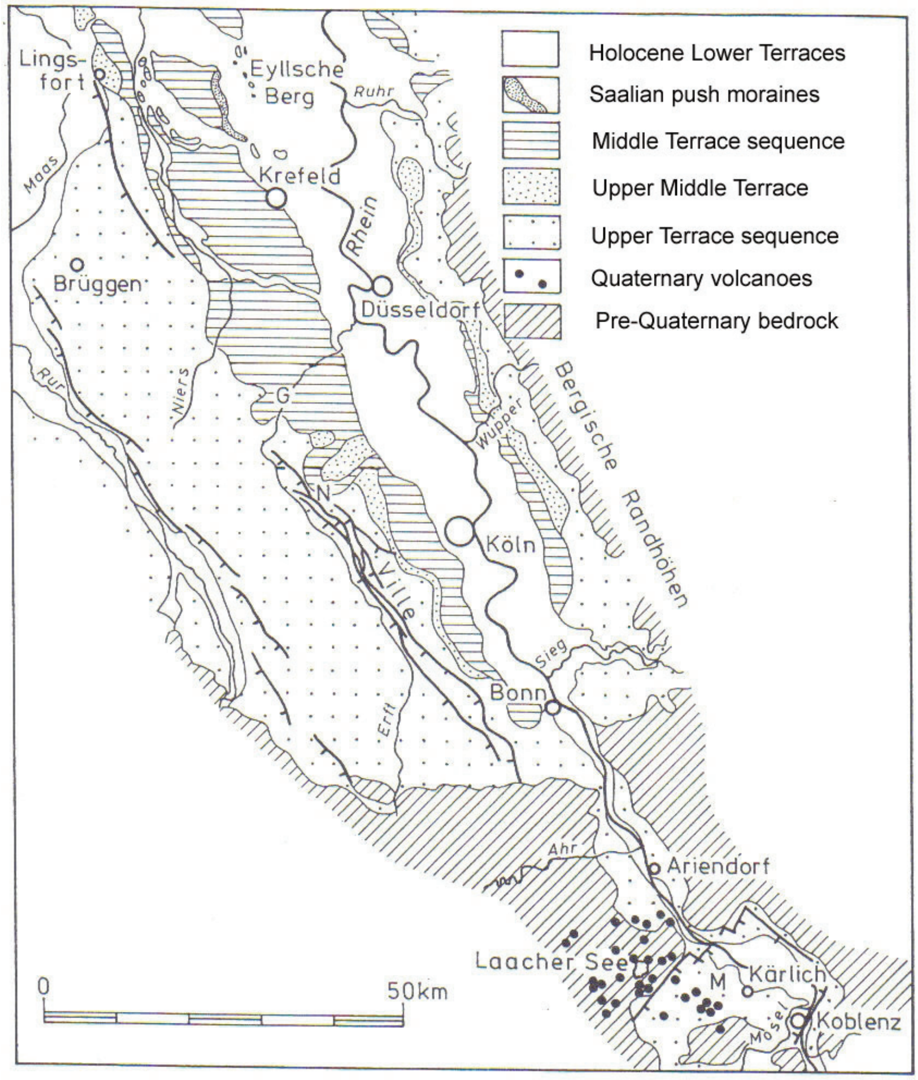


Figure 5.1: Kärlich and Ariendorf in the Middle Rhine region and the location of the terrace complexes along the river Rhine (Boenigk 1995). The Neuwied basin comprises a small (20x30 km) subsiding tectonic basin located in the centre of the Rhenish Shield.

- The Kärlich section, located in the Neuwied tectonic basin as part of the Middle Rhine type region in Germany.
- The Schöningen sections, located in the Subhercynic basin type region in Germany.

Because of their relatively long and well-dated sedimentary records and easy accessibility they give favourable opportunities for regional and interregional chronological correlations in Northwest and Central Europe. Kärlich, and adjacent Ariendorf, are type localities in the Middle Rhine region which, on the basis of tephrochronology from the East Eifel area, palaeomagnetic data and stratigraphical relationships between fluvial terrace gravel units and loess/palaeosol sequences, provide one of the best-dated composed Middle Pleistocene regional stratigraphies with interregional correlation potential to the type areas in the Lower Rhine basin and the North Sea basin (*section 5.3*). Their locations are shown in *Fig.5.1*.

Another type locality with favourable local depositional and preservation conditions is that at Schöningen in the Subhercynic type region. Here and in the adjacent Thuringian basin type region, several lacustrine sequences preserved in small-scale sedimentary basins (glacial lakes, solution hollows) as well as travertine sequences, rich in fossils, are interstratified between wide-spread Elsterian and Saalian glacial sequences. These fossiliferous non-glacial sequences may clarify the number and succession of warm climatic intervals during the late Middle Pleistocene (*section 5.3.2*).

5.2 Middle Pleistocene stratigraphy of the Middle Rhine type region: the sections at Kärlich, Ariendorf and Miesenheim

The Pleistocene stratigraphy in the Rhine valley, where it crosses the Rhenish Shield and the Middle Rhine Neuwied tectonic basin, is predominantly preserved beneath a series of local morphological terraces resting on Carboniferous and Devonian bedrock (*Fig. 5.2*). The terraces consist of fluvial sand and gravel deposits on which subaerial (reworked) aeolian, deluvial and colluvial deposits are superimposed. The sedimentary units are generally bounded by erosional and subaerial unconformities. Notwithstanding this discontinuity and diversity, the Middle Rhine sequence provides a long sedimentary record covering significant parts of the Middle Pleistocene and reflecting multiple responses to both regional tectonics (isostatic uplift and fault tectonics) and climatic fluctuation. In *Figure 5.2* the basic three-fold subdivision of terrace sediment complexes is shown.

As introduced by E. Kaiser (1903) the three-fold subdivision of the coarse-grained terrace series is based on the connected altitudinal positions of the erosional lower base of the terrace sediments. The following groups of terraces are recognised:

- *Hauptterrassenfolge or Upper Terrace Sequence* of which the lower base terrace steps are located above the shoulder of the entrenched Middle Rhine valley (Through valley terraces in *Fig. 5.2*) and extending to the southern part of the Lower Rhine Embayment (LRE).

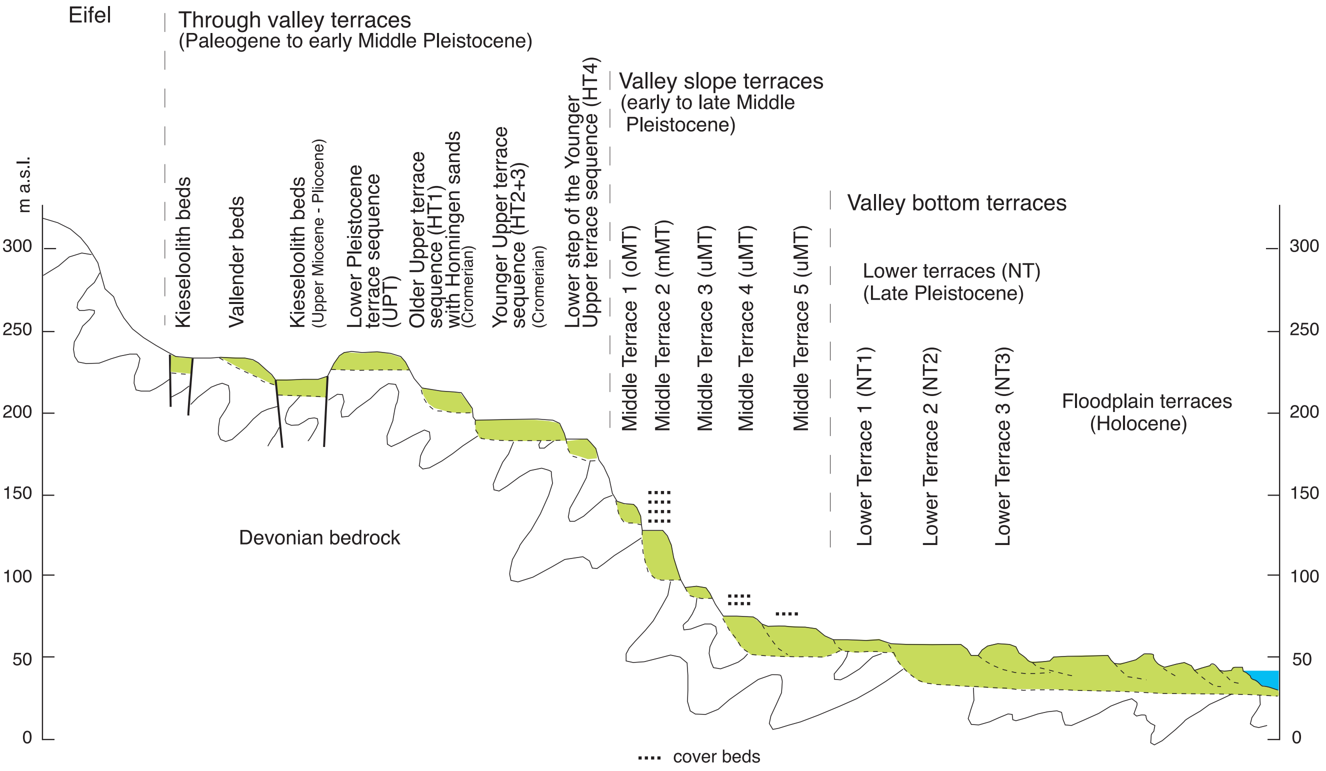


Figure 5.2: Schematic cross-section of the lower Middle Rhine valley (after Schirmer 1995) in which the subdivision and terminology of the terrace sequence is summarised and roughly ordered in time.

- *Mittelterrassenfolge or Middle Terrace Sequence*, of which the lower base steps are located along the slopes of the entrenched Middle Rhine valley (Valley slope terraces in *Fig. 5.2*) and in the southern part of the LRE.
- *Niederterrassenfolge or Lower Terrace Sequence*: comprises all alluvial terraces of lower base steps which are located just above or at the present floodplain level (Valley bottom terraces in *Fig. 5.2*).

This highest level subdivision for the terrace gravel series in the Middle Rhine valley still holds since the morphological position of their basal unconformities merely reflects the long-term trend of fluvial response[1] to tectonic phases of continual but varying uplift rates in the Rhenish Massif/Ardennes.

Besides morphostratigraphical criteria, further subdivision within this three-fold framework for the Middle Rhine terrace sequence has been based on lithological and petrographical characteristics of the different aggradation levels. Sedimentology and petrography (particularly) of the lower Middle Rhine terrace units have been reviewed in Kaiser (1903), Jungbluth (1918), Quitzow (1956), Bibus and Semmel (1977), Bibus (1980), Schirmer (1990) and most recently in Hoselmann (1994) and Schirmer (1995). After Hoselmann (1994), the *Hauptterrassen* Sequence in the northern part of the Middle Rhine type region is further subdivided into:
- *Unterpleistozäne Terrassen (UPT)* / Lower Pleistocene Terraces,
- *Ältere Hauptterrasse (äHT)* / Older Upper Terrace (= HT1 in the LRE),
- *Jüngere Hauptterrasse (jHT)* / Younger Upper Terrace (= HT2+3 in the LRE),
- *Unterstufe der jüngere Hauptterrasse (ujHT) /* lower step of the Younger Upper Terrace (= HT4 in the LRE).

They have their equivalents in the southern part of the Middle Rhine region (the tR-terrace sequence). With the exception of the latter two terraces, these generally are not very well preserved and affected by many local post-depositional tectonic displacements, complicating correlation with other parts of the Rhine drainage basin.

Vertical distances between the Middle Rhine terrace gravel units start to increase from the last but one Hauptterrasse: from the jHT to ujHT with levels at about 175 m a.s.l., changing over into the Middle Terrace (valley slope) Sequence. Although these coincide with strong uplift rates in the Rhenish Shield, imputed by a late Alpine orogenesis - the 'late Quaternary crisis'-, they are well-developed aggradational series which according to their different connected topographical positions of their base levels traditionally are divided into three main subunits:
- *Obere Mittelterrassen (oMT)* / Upper Middle Terraces corresponding to Middle Terrace 1 (MT1) in *Fig. 5.2*,
- *Mittlere Mittelterrassen (mMT)* / Middle Middle Terraces corresponding to Middle Terrace 2 (MT2) in *Fig. 5.2*,
- *Untere Mittelterrassen (uMT)*/Lower Middle Terraces which is further subdivided into Middle Terraces 3, 4 and 5 (MT3, 4 and 5) in *Fig. 5.2*.

At present the dating of the terrace stratigraphy and the palaeoclimatic and environmental history of the Middle Rhine type region is primarily based on:
- The stratigraphical interpretation of the overlying loess/palaeosol series above the various terrace gravel surfaces.
- Independent dating methods such as:
  - Palaeomagnetic measurements for determining the position of the major geomagnetic reversals (e.g. Brunhes/Matuyama) and excursions in the stratigraphical sequences,
  - Tephrostratigraphy and chronology supporting age control by radiometric dating.

Because radiometric dating has improved the Middle Pleistocene subdivision enormously since the 1950s a short review is given here. Frechen and Lippolt (1965) dated the start of volcanic activity in the East Eifel region at about 570 ka. Schminke and Mertes (1979) date the first volcanism in the area at 670 ka. Based on mineralogical composition of the tephras and dates, Van den Bogaard and Schminke (1990) distinguished six phases of volcanic activity within the East Eifel region (*Figure 5.9*). The Rieden phase (phase 3) is the best dated oldest phase as yet distinguished. Lippolt, Fuhrmann and Hradetzky (1986) suggest that these pyroxene-rich volcanics began at about 500-450 ka. Tephra beds intercalating and topping the mMT gravel complex at Ariendorf (*section 5.2.4*) are dated at *ca*. 490 ka (Van den Bogaard and Schminke 1990) rather than 420 ka (Fuhrmann 1983). The latter date indicates a maximum age for their aggradation. The youngest date of the Rieden phase, about 400-370 ka, is that for the *Brockentuff* breccia bed at Kärlich.

Pyroclastic ash and tuff beds intercalating the local Middle and Late Pleistocene sequences are, as shown above, also regionally important time markers because volcanic heavy minerals are incorporated in syn- and post-sedimentary subaerial and fluvial units. Their ages are even of extraregional significance since fluvial deposits of the Rhine downstream of the East Eifel region contain large amounts of volcanic minerals providing indirect dating possibilities via heavy-mineral analysis. The periodic interfering phases of extensive volcanic activity, highly facilitated regional chronological control. The first aggradation phase of the *Mittelterrassen* series is related to the onset of volcanic activity in the East Eifel region. Their heavy-mineral assemblages are, in comparison with the *Hauptterrassen*, characterised by high percentages of volcanic minerals of which the oMT-spectra are dominated by brown hornblende and the mMT-spectra by pyroxenes.

Superimposed on the river-terrace framework, the regional Middle Pleistocene stratigraphy is largely constructed from two long unconformity-bounded subaerial sequences, interstratified by tephra beds from the adjacent East Eifel region. These sequences have been preserved in relatively sheltered morphological situations which are more or less successive in time:
- the Kärlich section, where a stacked, lower Middle Pleistocene sequence has been preserved based by a gravel unit of the Upper Terrace Sequence (*i.c.*. the *jüngere Hauptterrasse* = tR5), in which the Brunhes/Matuyama reversal is present. This sequence is overlain by a compact tuff breccia ('*Brockentuff*') dated at about 396 ± 20 ka (Van den Bogaard *et al*. 1989),
- the Ariendorf section, which is a multiple, upper Middle and Late Pleistocene subaerial sequence overlying the *mittlere Mittelterrasse* (= tR8). This terrace gravel unit is mineralogically characterised by a dominance of pyroxenes and is overlain by tephra beds dated between 490 - 400 ka (Van den Bogaard and Schminke 1990).

Another important stratigraphical section is Miesenheim I.

The composed sequences of these key sections will be described in the next sections. Their local stratigraphies are starting points for interregional event- stratigraphical correlation downstream of the river Rhine to the North Sea basin of which a compilation is shown in *Fig. 5.10*.

5.2.1 The Kärlich section

[a] Geological setting and stratigraphy

The section in the Kärlich clay pit (coordinates: 50.24 N, 7.21 E) is located at the northeastern end of a dissected terrace surface which forms a 4 km long promontory in the SW part of the Middle Rhine Neuwied basin (*Fig. 5.1*). This terrace surface has a height of about 200 m a.s.l. which is about 140 m above the present Rhine course crossing the Middle Rhine Neuwied basin. The upper 30 to 35 m of the section consist of Pleistocene strata unconformably resting on over 50 m thick Tertiary deposits.

The pit has a reputation as a key-stratigraphical section for the early Middle Pleistocene stratigraphy and has been studied since 1913 (Mordziol 1913, Pohlig 1913). The most comprehensive studies were by Brunnacker *et al.* (1969) and based on a then fresh, 30 m high exposure in the NW-part of the pit which was cut over 300 m in length (*Fig. 5.3*).

The subdivision of the section is mainly based on lithostratigraphy, supported by petrographical, pedostratigraphical and biostratigraphical evidence. Brunnacker *et al.* (1969) distinguished eight Pleistocene stratigraphical units in this section numbered from the base upwards, unit A to H. They are topped and protected by an up to 8 m thick tuff breccia layer, the '*Brockentuff*', which forms the base of unit J (*Fig. 5.3*).

Large parts of the main exposure are now obscured. Further investigations have therefore mainly been carried out on the basis of vertical profiles cut through the section by the research teams of Professor Bosinski (University of Cologne) and of Professor Boenigk (University of Cologne). The investigations revealed a wealth of multidisciplinary evidence: sedimentological (Frechen & Rosauer 1959, Brunnacker *et al.* 1969, Schirmer 1970, Sefkow 1986), mineralogical (Razi Rad 1976), palaeomagnetical (Koci *et al.* 1973, Boenigk *et al.* 1974, Brunnacker *et al.* 1976, Fromm, 1987), palaeontological (Würges 1984, Van Kolfschoten 1988, Van Kolfschoten *et al.* 1990, E. Turner 1989, 1991, Roth 1995), pedological/micromorphological (Frechen and Rosauer 1959, Mückenhausen 1959, Brunnacker *et al.* 1969), tephrochronological (Van den Bogaard & Schminke 1989) and archaeological (Bosinski *et al.* 1980, Vollbrecht 1994). Most of this information has been summarised by Schirmer (*ed.* 1990).

Notwithstanding that the lowermost unit A has been badly exposed, and that the distinction between the units C and D in the section is not always clear, the initial subdivision has been confirmed several times by field observations in the almost thirty years after publication and has become a reference. A generalised section based on this once well-exposed wall is shown in *Fig. 5.4a*, taken from Gaudzinsky *et al.* (1996), to which slight modifications are introduced from sections which became exposed during later excavations.

[b] Unconformity-bounded sequence stratigraphical subdivision of the lithofacies associations

As Boenigk and Frechen (2001) have also stressed, the Kärlich section shows a record of discontinuous deposition alternating with substantial erosion and soil formation. Most indicative of the hiatal breaks in the stratigraphical succession are the subaerial erosional and exposure unconformities which bound the local-scale (litho)stratigraphical units distinguished by Brunnacker *et al.* (1969). These discontinuities, although irregular, can be well followed throughout the schematical section shown in *Fig. 5.4a*. They indicate that earlier exposed sediments have been partly removed, reworked or modified. Post-depositional pedogenic fea-

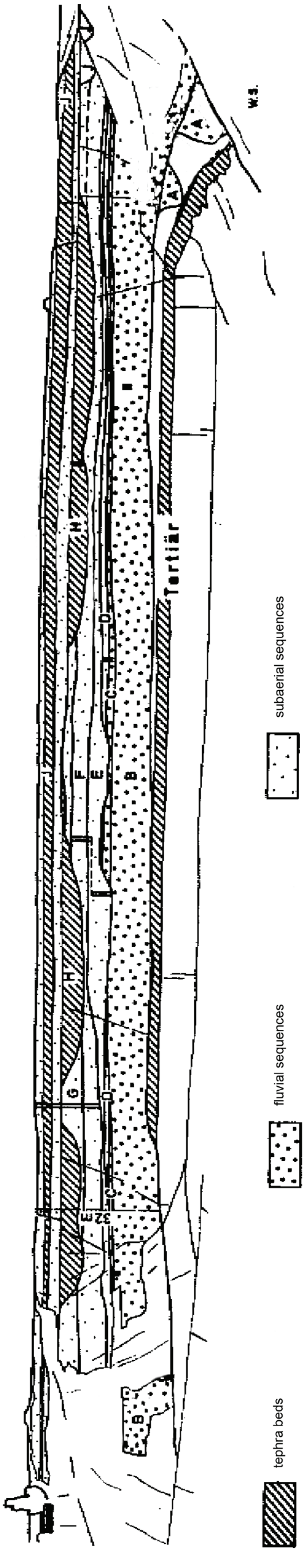


Figure 5.3: The classical Kärlich section (from Brunnacker *et al.* 1969).

tures, which can frequently be observed in the upper parts of the preserved beds, point to periods of stable land surfaces and subaerial exposure, under relatively temperate conditions. Accordingly, the net depositional levels intervening between these major periods of prevailing erosional and soil-forming processes, can be assigned unconformity-bounded units at a synthem level. In turn, they can be further subdivided into subsynthems confined by minor/local-scale reactivation surfaces and built of largely similar lithofacies associations of often various laterally changing lithofacies units.

In *Fig. 5.4a* all observed lithofacies associations combined in the synthems have been accumulated on a metre scale. On the basis of lithogenetic interpretation and the multidisciplinary data included in these local units, relationships to major depositional environments and erosional/non-depositional interruptions may be attached to each of the subsynthems. Together with the relatively known chronological control, a chronostratigraphical scheme (*Fig. 5.4b*) has then been compiled in which sedimentary parasequences as well as the unconformities, filling the gaps in the sedimentation, are given on a relative time scale. Whereas the unconformable surfaces have no thickness in *Fig. 5.4a*, their significance becomes better visualised with relative time plotted on the vertical axis, i.e. as virtual temporal units (hiatal breaks) alternating with the time intervals of (net) deposition[2]. The model contains many clues to the reconstruction of the successive changes of sedimentary environments and ecosystems responding to climatic and tectonic stratigraphical events/cycles which have been effective at different scales with regard to magnitudes and frequencies in this part of the Middle Rhine Neuwied basin.

The Kärlich section, underlying the '*Brockentuff*' bed, roughly consists of a two-fold sequence of a basal complex of predominantly coarse-grained lithofacies associations consisting of synthems deposited under subaquatic conditions in a fluvial environment (units A, B) changing over into an overlying series of fine-grained lithofacies associations formed in terrestrial mainly subaerial erosional/denudational and aeolian environments (units C, D up to H).
Bounding surfaces, main litho- and biofacies characteristics, in particular heavy-mineral contents and mammal fossil assemblages, and syn- and post-depositional features will be briefly described below. Detailed descriptions of the lithostratigraphical units *sensu* Brunnacker *et al*. (1969) are given in Boenigk and Frechen (2001). Here emphasis is put on criteria that provide information on local and regional climatic conditions, relevant chronostratigraphical evidence and the relationships to large-scale (glacial-interglacial) climatic and tectonic cycles.

[c] Fluvial genetic sequence units and unconformities (Units Kärlich A and B)

The Quaternary base at Kärlich is formed by a (subhorizontal) major erosional unconformity, representing a break of millions of years, above which a 10-14 m thick fluvial gravel complex rests. Up to three synthems (*Kärlich A*, *Ba and Bb*) are recognised each consisting of fining upward aggradation levels followed by a phase of subaerial exposure and soil development. Here the lithofacies associations are characterised by cross-bedded basal gravel and sand fining upwards into silts and clays. They are interpreted as subaquatic channel-fill sequences of braided river systems covered by flood loams. Bounding reactivation surfaces are rather weakly developed with the exception of the lowermost synthem unit A. This unit is unfortunately no longer exposed but the occasional channel fills were incised to 4 m into the Tertiary strata (Brunnacker *et al*. 1969). One of the basal channels consists predominantly of sand reworked from the Tertiary subsurface. They are generally described as fining upward channel-fill deposits containing material with a strong river Moselle influence (Boenigk *et al*. 1996). In contrast to the overlying aggradation levels of unit *B*, the unit *A* channel gravels and sands, as observed by Brunnacker *et al*. (1969), display very high angle cross bedding (40 to 50 degrees). This suggests that they may be tilted by intermediate tectonic dislocation or by normal faulting due to fluvial activity. The suggestion that part of unit *A* consists of tectonically dislocated parts of unit *Ba1* and therefore are not older channel fills (*cf*. Van den Bogaard *et al*. 1989) is, however, not proven since the channels were at the time located at the Rhine side of the pit and recent excavations show large normal faults in this part of the pit. The faults post-date the deposition of the '*Brockentuff*'. The fine-grained sediments in unit A are palaeomagnetically reversed, while the gravelly basal parts show normal polarity. They are also pedogenically overprinted (Koci *et al*. 1973, Boenigk *et al*. 1974, Fromm 1987). The latter may be due to post-depositional re-arrangement.

The remaining part (*B*) of the gravel complex can be followed over the entire section. The lowermost synthem unit *Ba* consists petrographically of up to 6 m thick, stratified coarse Rhine gravel topped by some 0.5 m sandy silts. Two subsynthems, the units *Ba1* and *Ba2*, can be distinguished, the latter of which is represented by a mixed sand and gravel bed showing cryogenetic features. The uppermost synthem unit *Bb* is about 2 m thick and comprises Moselle gravel overlain by laminated silts. Lower boundaries are reactivation surfaces, although not very intense (up to 2 m). Subaerial exposure of these former floodplain surfaces is confirmed by gleyed palaeosols of Bh-type (*i.c.* humic soils, '*Auenlehm*') in the upper parts of the deposits.

[d] Subaerial genetic sequence units and unconformities (Units C, D, E, F, G and H)

The basal gravel complex is overlain by a series of predominantly fine-grained lithofacies associations in which mixtures of silt and fine sand dominate. Lateral facies changes, as well as syn- and post-sedimentary structures, are common. Individual lithological units are numerous, further complicating straightforward interpretation into sedimentary cycles.

The sequence units C, D, E and F

The change from fluvial subaquatic environments to prevailing subaerial environmental conditions is not marked by a strong erosional boundary. This indicates to a gradual change of the major alluvial depositional environment of the Rhine and Moselle river system into a subaerial floodplain flat subenvironment with occasional floods, increasing aeolian and mass wasting/soliflual activity, alternating with pedogenic processes and bioturbation. Sediment input from then is of aeolian origin.
The palaeoenvironmental reconstruction can be determined from the fine-grained lithofacies associations of the units *Kärlich C* and *D* which can be followed over the entire section and constitute discontinuous beds with laterally changing fine-grained lithofacies associations. The lower boundaries of the units *C* and *D* are not very distinct. Within unit *C* at least two subunits have been deposited in a fluvial subenvironment of silt flats where, beyond the active Rhine channel floodplain, occasional floods occurred in combination with aeolian activity. Bioturbation and some reddening indicate to periods of non-deposition. The next lithofacies unit constitutes unit *Kärlich D* where silts and fine sands occur with horizons of carbonate concretions.

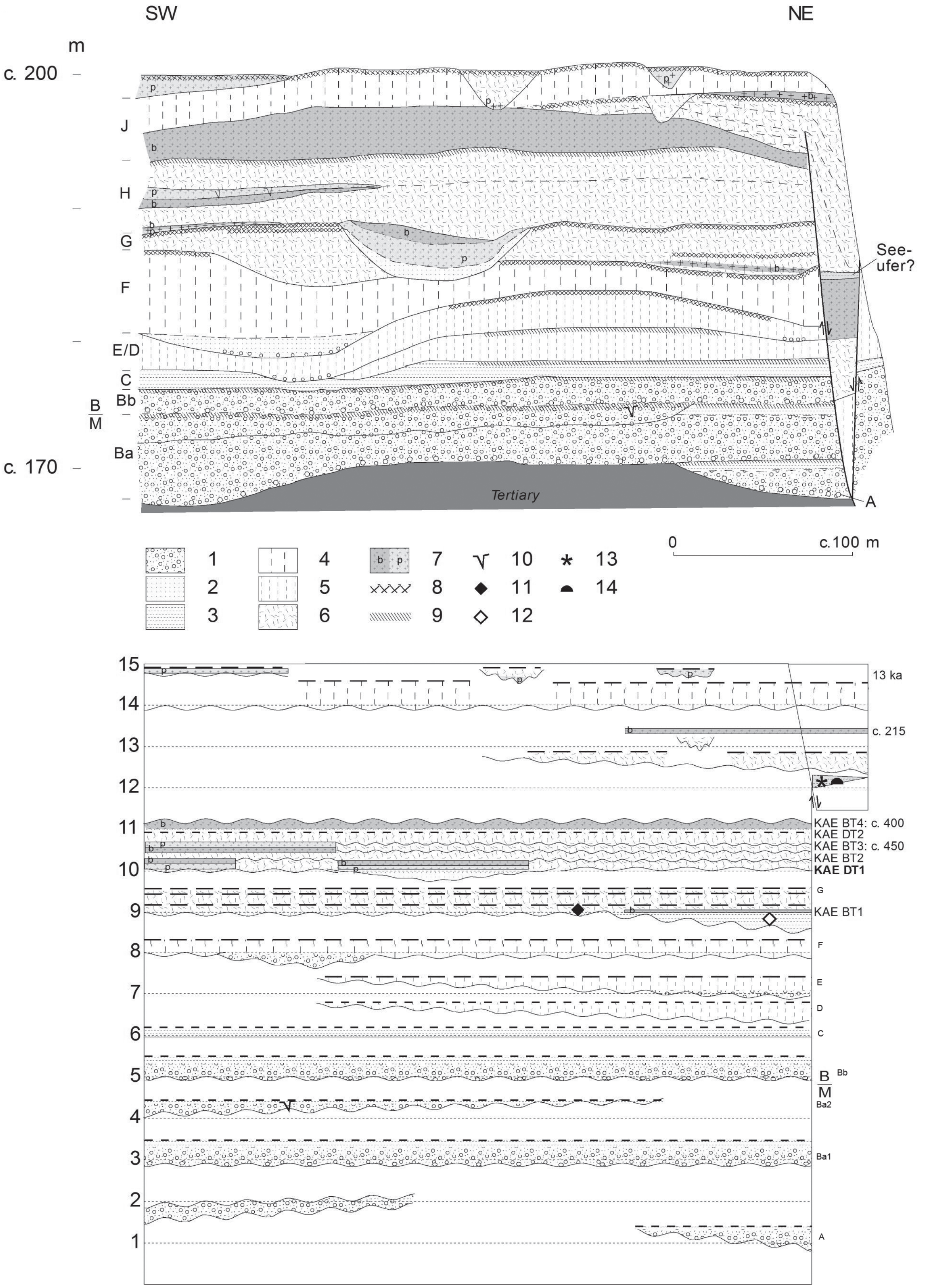


Figure 5.4: a) Lithostratigraphical model based on schematic section of Kärlich (Gaudzinsky *et al.* (1996); b) Interpreted chronostratigraphical model of the Kärlich section with unconformity-bounded sequence and containing bio- and chronostratigraphical information. 1) sand and gravel/ coarse-grained lithofacies,alluvial, 2) sand/fine-grained lithofacies, alluvial, 3) silt/fine-grained lithofacies, subaerial, reworked, 4) loess/aeolian, 5) silt and fine sand / fine-grained lithofacies, subaerial, 6) silt/ fine-grained lithofacies, colluvial, soliflual, 7) tephra: b-basaltic, p-pumice, 8) soil leached (forest-Bt), 9) soil humic (Bh), 10) cryogenic structure, 11) small mammal remains, 12) large mammal remains, 13) molluscan remains, terrestrial, 14) mollusc remains, fresh water.

Stronger erosional unconformities occur from unit *Kärlich E*. The units *Kärlich E* and *Kärlich F* are relatively uniform in composition and consist of coarse-grained basal 'lag' deposits fining upward into silts and fine sands. Reddened - to Bt-soils are developed in their upper parts. The sediments lack volcanic heavy minerals and contain loess-typical molluscs in the upper parts.

Unit *Kärlich E* consists of a basal sandy part rich in snail remnants, the so-called '*Muschel-*' or '*Schneckensande*', grading into silts, in which two laterally changing subunits can be observed which are fluvially reworked. The lower part also shows characteristics of aeolian sand, possibly derived from the Rhine floodplain. A weak soil is developed above but is missing in large parts of the section because of the major basal unconformity of the overlying unit *Kärlich F*. The latter break is recorded by erosional surfaces of which the stream beds are filled by gravelly 'lags' with reworked '*Oolietenkies*'. Following another unconformity, the upper part consists of loess and loess-like deposits with molluscs of *Columella* faunal type. This is the only unit which contains typical loess. *Kärlich F* is topped by a Bt-horizon of a para-brownearth.

The sequence units G and H

Following the most marked erosional unconformity, the units *Kärlich G* and *Kärlich H* are more complex units and differ in many ways from the underlying units.

Kärlich G consists of a multiple sedimentary succession of silty deluvial/colluvial and soliflual deposits laid down in an elongated depression. The origin of this small-scale basin is unknown. Since the Bt-horizon in unit *F* can be observed below the basin fill this may have occurred simultaneously or following the soil formation on the surface of this unit. Unit *G* lacks a reworked coarse-grained 'lag' deposit. In the small-scale basin environment at least five different lithofacies associations, bounded by subaerial unconformities, have been distinguished in the basin centre (Boenigk *et al*. 2000). They consist of sandy and clayey silts of which the upper parts are largely structureless and brown coloured by syn- and post-depositional pedogenic processes and bioturbation. Subaquatic conditions are also observed, in the so-called '*Seelöss*' lithofacies unit. Para-brownearth type Bt-horizons, partly pseudogleyed, are preserved in the first and last two (sub)synthems (*Kärlich G I* and *G IV* and *V*). In particular the forest soil remnants on the *Kärlich G IV* and *V* units are strongly developed. The palaeosol of *Kärlich G IV* constitutes the most pronounced one of the Kärlich section and represents the type *Kremser Soil cf.* Brunnacker *et al*. (1969). Since loess(-like) deposits or cryogenic features are absent there are no indications of a climatic glacial cycle in unit *Kärlich G*. Subunit *Kärlich G I* contains the first *Arvicola terrestris cantiana* small mammal remains in the section. Subunit *Kärlich G II* contains the first volcanic ash stratum (KAE-BT1) in the Kärlich section. The heavy-mineral composition is dominated by brown hornblende. Pyroxenes become abundant in the uppermost subunit *Kärlich G V*.

Unit *Kärlich H* forms another complex of unconformity-bounded and laterally changing lithofacies units. It can be subdivided into two subunits: *Kärlich H I* and *Kärlich H II* which are separated by a major unconformity. Up to nine sedimentary subunits separated by minor unconformities have been distinguished in *Kärlich H I*. Two basal subunits (*Kärlich H Ia,b*) of silt, sand and fine gravel are followed by a strong erosional unconformity which is irregular with channels cut into several older units. The channels are filled with basaltic tephra (KAE-DT1 and KAE-BT2) which can be easily recognised by their dark grey colour. They are mixed with and covered by silt/loess beds (*Kärlich H Ic*). Bioturbated '*Fliesserde*' (*Kärlich H Id,e*) followed by loess units (*Kärlich H If, g*) are intercalated by two more tephra layers (KAE-DT2 and KAE-BT3). *Kärlich H I* ends with a major unconformity on which pellet sand, '*Fliesserde*' and a Bt/Bh palaeosol of para-brownearth type, referred to as *Kärlich I Interglacial* by Boenigk (1995), have been developed. *Kärlich H II* comprises two further '*Fliesserde*' units (*Kärlich H IIa,b*) containing warm molluscan fauna assemblages and featuring pseudogley on top. The sequence then is overlain by the *Brockentuff* breccia bed.

[d] The sequence post-dating the Brockentuff-deposition: the Kärlich-Seeufer section

The younger part of the Kärlich section is best exposed in the northeastern part of the pit where archaeological excavations have taken place. The sequence is located close to the edge of the Rhine valley. Here the Kärlich terrace has been affected by dislocations and normal faulting due to tectonic activity, probably accompanying the Rieden phase volcanic eruptions, and oversteepening of the slopes. Major faults are identified post-dating the deposition of the *Brockentuff* (*Fig. 5.5*). In this small section the *Brockentuff* has been downwarped more than 10 m by a listric normal fault which could be followed northwards over a distance of 50 m to the main pit exposure. The fault is probably also part of a local landslide because the downfaulted side is proximally tilted. The dislocated *Brockentuff* bed is unconformably overlain by silty deposits, the upper part of which is laminated. This unconformity is accompanied by an ice-wedge cast infilled by the overlying silt. Both the ice wedge cast and the silt accumulation indicate to a cryogenic/periglacial environment with at least for some time continuous permafrost conditions prior to the faulting. These observations can probably further elucidate the local chronostratigraphical framework after the deposition of the *Brockentuff*, dated at about 396 ± 20 ka (Van den Bogaard *et al*. 1989), and to the origin of the lacustrine sequence of Kärlich-Seeufer. The latter is located in a former depression in the southern part of the clay pit. The Kärlich-Seeufer sequence consists of solifluction and lacustrine deposits above displaced and reworked *Brockentuff* material, over 10 m thick, accumulated in this small basin. The site has yielded important palynological, archaeological and palaeontological evidence (Gaudzinsky *et al*. 1996) and has been the subject of several studies (Urban 1983, Bittmann 1992, Gaudzinsky *et al*. 1996). The pollen record of the lake deposits contains a late-temperate forest climax. The presence of *Azolla filiculoides* and *Celtis* indicate a pre-Eemian warm event. The absence of *Pterocarya* contradicts a correlation with the Holsteinian climatic optimum. Because of a striking resemblance, Bittmann (1992) and Bittmann & Müller (1996) consider the Kärlich-Seeufer pollen diagram to be equivalent to the upper part of the Bilshausen solution lake pollen record located in Lower Saxony. Moreover, the latter sequence contains a tephra stratum which indeed may indicate volcanic activity in the Eifel region, although long distance correlations should be carefully examined. Re-interpretation of the original data from the Bilshausen cores by Bittmann & Müller (1996) showed that there is no duplicate stratum present in this sequence implying that, contrary to earlier published results, only one forest stage climax is recorded. The associated warm event is equated by these authors to MIS 11. They also suggest a stratigraphical position intermediate of the Cromerian IV and Holsteinian warm stages. Because of the origin of both lake sequences their pollen records need not necessarily be associated with a warm climatic optimum succeeding a major glaciation, i.e. the Holsteinian Stage. The Kärlich-Seeufer section represents the first climatic optimum following the local landslide which occurred after the deposition of the *Brockentuff* at about 400 ka. This warm event may therefore well

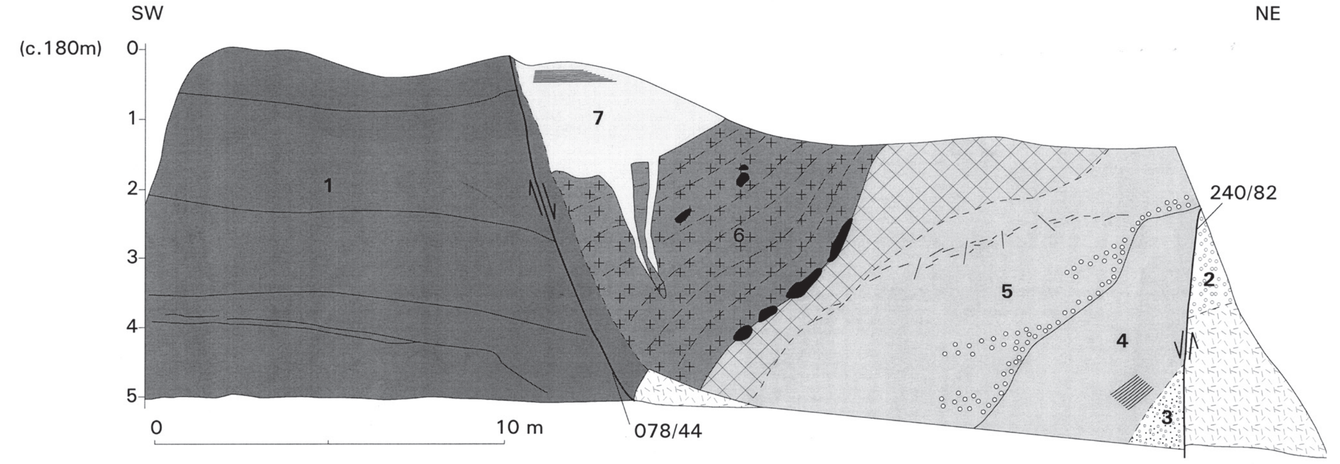


Figure 5.5: Section from a small outcrop near the Kärlich-Seeufer section close to the edge of the Rhine valley showing normal faults. 1. Tertiary clay ('Knubb'), 2. stratified sand and gravel, 3. sand and gravel (unit B?), 4. silt, partly laminated (unit C/D?), 5. silt with gravelly base ('Kieseloöliet'?) and Bt-type soil on top (unit E?), 6. 'Brockentuff' breccia tephra, 7. silt, ice-wedge cast at base.

corroborate a post-Holsteinian age and allow for correlation with the Landos warm Stage from the Lac du Bouchet lacustrine record and for correlation with MIS 9.

[e] Chronostratigraphical control

The major part of the Kärlich section is palaeomagnetically and tephrochronologically roughly dated between 800 and 400 ka. Chronostratigraphical control at Kärlich is achieved by:

- The occurrence of the Brunhes/Matuyama geomagnetic reversal in the basal gravel sequence (between the syntems *Kärlich Ba(2)* and *Bb*).
- The presence of a tephra bed in unit *Kärlich G* and heavy-mineral assemblages dominated by brown hornblende in the lower subunits *of Kärlich G*, indicating to the start of volcanic activity in the East Eifel region between 600-700 ka.
- The first occurrence of pyroxenes in the heavy-mineral assemblages from subunit *Kärlich G V* which may correspond to the Rieden phase of volcanic activity and which took place from about 500-450 ka (Boenigk and Frechen, 2001).
- Dating of basalt and pumice tephras in unit *Kärlich H*. Several of these marker beds have been dated by means of the K/Ar and Ar/Ar methods (Frechen and Lippolt 1965, Van den Bogaard and Schminke 1990). Although age determinations have not been very consistent due to various methods and techniques, the dates of the KAE-tephras in subsynthem *Kärlich H1* appear to concentrate around 450 ka. Most important is the interference of volcanic ash layers within the loess sequences that indicate deposition during cold climate conditions.
- Dating of the Kärlich *Brockentuff* most recently dated at *c*. 396 ± 20 ka (Van den Bogaard *et al*. 1989).
- Relative biostratigraphical time markers of interregional importance:
  - small mammals: FAD of *Arvicola terrestris cantiana* in the basal part of unit *Kärlich G (G I)*,
  - large mammals: the first occurrence of *Elephas (Palaeoloxodon) antiquus* in unit *Kärlich H II*, also present at Kärlich-Seeufer; depositional units *Kärlich E*, *F* and *G* contain *Megaloceros verticornis* which is generally found in pre-Elsterian sequences,
  - palaeobotanical evidence: absence of *Pterocarya* in the late-temperate vegetational zone of the Kärlich-Seeufer pollen sequence, indicating a post-Holsteinian age.

This information is included in the chronostratigraphical model for the Kärlich section in *Fig. 5.4b*. and is also given in the correlation scheme of *Fig. 5.9*.

[f] Event-stratigraphical interpretation and regional correlation (Middle Rhine type region)

On the basis of the information from the chronostratigraphical model, large-scale correlation criteria and within the chronostratigraphical framework of *Fig. 5.4b*, some regional climatic (and tectonic) event-stratigraphical implications are:

- The gravel complex of *Kärlich B* coincides with the *Hauptterrassenfolge* / Upper Terrace Sequence of the Middle Rhine and Moselle (Brunnacker *et al*. 1969), i.e. the units *Kärlich A*, *Ba1* and *Ba2* correspond to the äHT (= tR4 = HT1, and unit *Kärlich Bb* = jHT (= tR5 = HT 2+3 (showing normal polarity). The Brunhes/Matuyama boundary is found at the transition of the gravel units *Ba2* and *Bb* (Koci *et al*. 1973)). The first terrace deposits of Brunhes Chron age in the MR Neuwied basin belong to the Younger Upper Terrace unit (jHT=tR5). They occur at many sites at the basin margin (Schirmer 1990). At Kärlich, they are represented by unit *Bb* and form the base of the overlying loess and solifluction sequence. Since unit *Kärlich Bb* is of Moselle origin it may represent an alluvial-fan, deposited as a consequence of changing river courses. The 3 aggradational levels in unit *B* document stratigraphical events associated with an increase of sediment supply in the fluvial environment. This environment coincided with cold climate conditions and maybe due to accelerated uplift of the surrounding Rhenish Shield. Their superposition indicates that they are preserved under relatively stable or subsiding tectonic conditions in the Middle Rhine Neuwied basin, prior to the tectonic event of strong uplift resulting in the ujHT and younger valley slope terraces.
- The sequence continues with the loess/palaeosol stratigraphy in which regional uplift trends can be identified by erosional unconformities separating climate-related fine-grained depositional sequences. These sequences originate from aeolian and volcanic environments which are to a great degree syn- or post-depositionally reworked by a combination of local stream activity, mass wasting processes and pedogenic processes. Two main erosional surfaces are found at the base of unit *G* and of unit *H*. They may be correlated with the strong unconformities separating the terrace sequences of the ujHT/oMT and the oMT/mMT.

They also coincide with the formation of brown hornblende-rich volcanic minerals and pyroxene-rich heavy minerals, respectively.
- A large-scale subaerial depositional sequence has to contain an erosional base, reworked washed sediments, solifluction deposits, an aeolian unit, solifluction deposits and a forest Bt-soil complex at the top. Only in the units *Kärlich E*, *Kärlich F* and probably *Kärlich H I* are aeolian environments cold and dry enough to permit a link with large-scale periglacial desert event conditions. Unit *Kärlich F* coincides with periglacial desert conditions prior to the volcanic East Eifel eruption phases and prior to the FAD of *Arvicola terrestris cantiana*. Although correlation of fluvial and subaerial sequences in Central and Northwest Europe is problematic because of tectonic activity interfering with climate, unit *Kärlich F* most probably corresponds to Central European loess cycle H, which is correlative with the Donian glaciation of 'Cromerian Complex' age. Subunit *Kärlich H I* then corresponds to CE loess sequence F and the Elsterian glaciation.
- The intense (polycyclic) soil formation in unit *Kärlich G*, and the absence of cryogenic structures in the unit may point to a long-lasting period of warm climate conditions.

5.2.2 The Ariendorf section

[a] Geological setting and stratigraphy

A second well-documented reference section in the Middle Rhine type region is the Karl Schneider gravel pit (coordinates: 50.31 N, 7.18 E) near the village of Ariendorf. It is located just north of the Neuwied basin in a terrace surface on the eastern side of the entrenched Middle Rhine valley. Up to 30 metres of sand and gravel deposits are exposed in the quarry, resting unconformably on Devonian bedrock. They are overlain by some 15 metres of loess/palaeosol sequences in which at different levels volcanic ashes and pumices are intercalated. The terrace surface is at 140 m above m.s.l. which is some 60 m above the present Rhine valley floor. Sedimentological investigations started in the beginning of the 1970s after the discovery of large mammal fossil remains. The results have been published in a paper on the Central Rhineland stratigraphy by Brunnacker *et al*. (1975). Another study based on the early pit exposures was undertaken by Bibus (1979). The most comprehensive geological section of Ariendorf was described by Haesaerts (in Schirmer 1990). A history of the investigations at Ariendorf is reviewed in E. Turner (1997) who concludes with a revised stratigraphical interpretation.

The lithostratigraphical succession is in many ways similar to that of Kärlich: a coarse-grained fluvial sequence, where after abandonment by the river an overlying subaerial sequence has been preserved reflecting different climatic cycles (*Fig. 5.6*). Lithostratigraphical units and terminology follow the initial subdivision of Brunnacker *et al*. (1975). They comprise the *Leubsdorf Terrace* gravel, pumice beds below and on top of the Ariendorf warm Stage soil and three loess sequences (*Löss Decke (LD)I*, *II* and *III*) of which another pumice bed is covering the fossil soil developed in *LD II*.

Haesaerts (1990) distinguished two depositional phases within the original *LD I* loess unit, of which the lowermost (the *LD 0* or '*Haesaerts*' loess) contained a Bt forest soil complex. His sche-

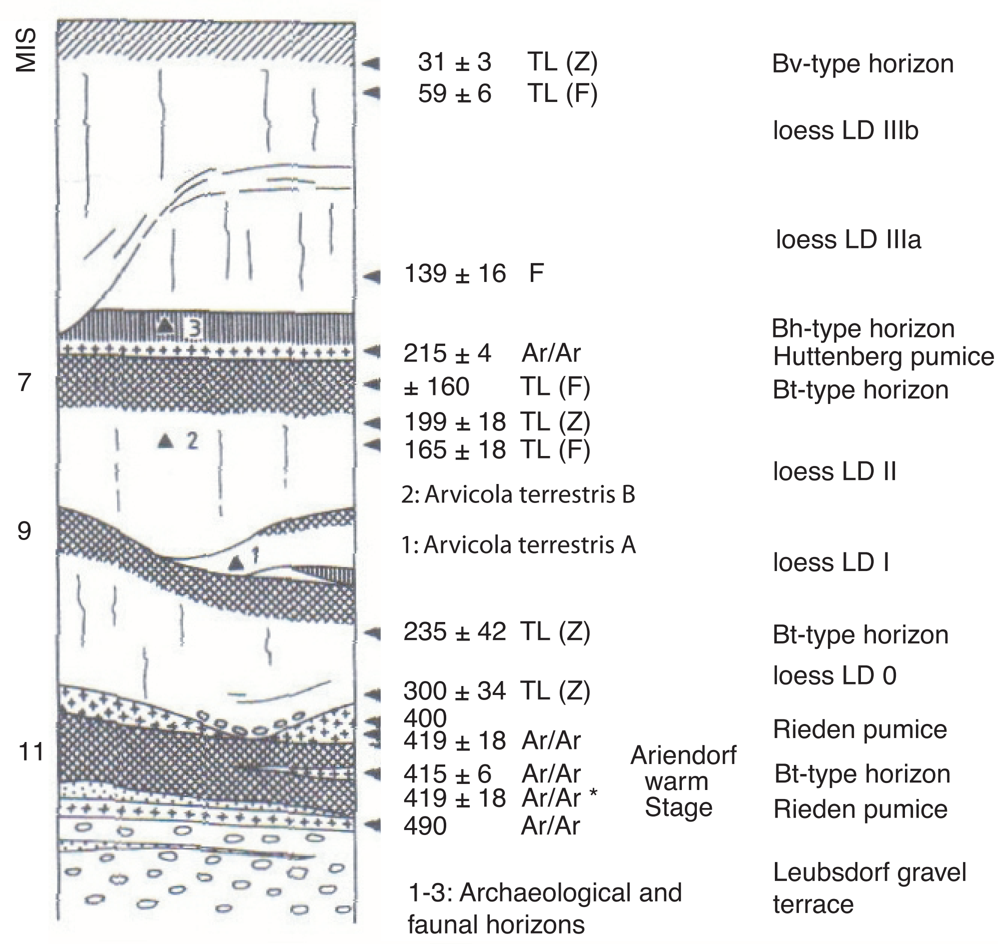


Figure 5.6: The Ariendorf section: stratigraphy, geochronological dates, faunal horizons and correlation of the fossil forest soils with the MIS (from Schirmer 1995). Ar/Ar dates by Van den Bogaard and Schminke (1990); Ar/Ar* date by Lippolt, Fuhrmann and Hradetsky (1986); F = Tl dating by Frechen (1993) and Z = Tl dating by Zöller *et al.* (1988).

matical section, recorded in 1988, is used for a lithostratigraphical model on the basis of bounding unconformities (*Fig. 5.7a*). From this section a chronostratigraphical model has been reconstructed in *Fig. 5.7b*, including tephrochronological data and biostratigraphical evidence from the three archaeological and faunal horizons.

[b] Fluvial depositional sequence units and unconformities

The Leubsdorf terrace complex consists of one aggradation phase of coarse-grained lithofacies assemblages, topped by fine sand and silt (flood loams). The thick basal gravels comprise stratified channel-fill deposits of which the lower boundary has been downcut into bedrock. They are intercalated by a volcanic ash bed (ARI-DT1). Synsedimentary cryogenic features in the sand and gravel bed above this horizon prove deposition under cold-climate conditions. The terrace gravel unit is mineralogically characterised by a dominance of pyroxenes. Within the flood loam on top of the gravels a fossil soil (Bt of a brownearth) has been developed. Two pumice tephra beds (ARI-DT2 and ARI-DT3), described as '*Selbergit tuff*', are stratified within and above the soil complex. Brunnacker *et al*. (1975) report that these volcanic ashes and pumices are also weathered and assigned both the flood loam and the tephra series to the Ariendorf (Stage) Interglacial.

[c] Subaerial depositional sequence units and unconformities

Haesaerts (1990, *Fig. 5.7a*) identified four subaerial depositional cycles of fine-grained lithofacies above the gravels and the Ariendorf Stage deposits, bounded by erosional unconformities and soil complexes. These synthems consist of silt and fine sand beds which have often been reworked by solifluction. Most lithofacies associations can be characterised as '*Schwemmlöss*'. Typical loess is not present. Molluscan assemblages and some larger mammal faunas indicate to cold-climatic conditions during deposition. The lowermost 'loess unit of Haesaerts' (= *Ariendorf LD 0*) is based by locally derived gravel 'lags'. It is underlain by a small channel infill and another unconformity-bounded sandy unit both showing red-brown colouration (*Fig.5.7b*). These warm-stage deposits, stratified above the upper ARI-DT3 tephra bed, were recovered in the 1980s and considered to belong to the Ariendorf (Stage) Interglacial (Bosinski *et al*. 1983). Their upper boundary has been extensively cryoturbated.

Unit *Ariendorf LD I* consists of laterally changing sandy silt and contains an archaelogical horizon at its base with micromammal assemblages. The soil complex occurring in its upper part is not well developed and discontinuous in the sections of *Fig. 5.7*. The units *LD I* and *LD II* are separated by a major erosional unconformity. The erosional base of *Ariendorf LD II* cuts into the lowermost subaerial unit *Ariendorf LD 0*. Within the loess-like unit *Ariendorf LD II* two minor unconformities can be distinguished. A second archaeological level found in the upper subsynthem contains faunal remains and a small lithic artefact assemblage. Subaerial unit *LD II* is topped by a Bt-horizon of a parabrownearth and a humic soil layer, the latter containing a third archaeological horizon. The palaeosol units are interbedded by a 15 cm thick pumice tephra (ARI-DT4), the *Hüttenberg* pumice. According to Boenigk and Frechen (1997) this tephra is situated in the basal part of the humic soil. Finally, the uppermost over 8 m thick unit *Ariendorf LDIII* is subdivided by a major erosional unconformity into two subaerial synthems: *LD IIIa* and *LD IIIb*. They consist of silt and fine sand showing many solifluction structures ('*Fliess-Erde*') and reworked sandy and gravelly horizons. In the upper part of subunit *LD IIIa* two weak humic horizons are present. Since there is no evidence of an intermediate fossil forest soil, it is not sure if the subunits represent two large-scale climatic cycles.

[d] Chronostratigraphical control

The multiple, late Middle and Late Pleistocene subaerial sequence at Ariendorf is chronostratigraphically constrained by:

- Ar/Ar dates of the intercalated tephra beds. ARI-DT1 is dated at *c*. 490 ka (Van den Bogaard and Schminke 1990). The two pumice tephras ('*Selbergit tuff*') found on top of the basal gravel complex are dated to around 450 ka and 410 ka, respectively (Van den Bogaard and Schminke 1990). Earlier dating of the younger tephra gave an age of about 420 ka (Fuhrmann 1983). They are attributed to eruptive phase 3, the Rieden phase, which lasted from about 500 to 400 ka. The *Hüttenberg* tephra, deposited above the soil complex in loess bed *LD II*, is mineralogically similar to volcanic products of the Wehrer eruptive phase which took place at about 215 ka (Van den Bogaard and Schminke 1990).
- TL dates from samples of the subaerial units *Ariendorf LD I*, *LD II* and *LD III* (Frechen 1991). TL dates from the upper part (b) of *LD III* points to deposition during the Weichselian Stage. Dates of subunit *IIIa* gave ages from about 90 to 140 ka, those from *LD II* and *LD III* were over 160 ka respectively 235 ka. The various TL dates (*Fig. 5.7*), older than the TL-dating limit of about 125 ka, are contradictory to the Ar/Ar dates of the tephra layers. Although they seem consistent with the stratigraphy, they are not reliable.
- Relative dates from micromammal assemblages from the archaeological horizons in *Ariendorf LD I* and *LD II*. Molar characteristics of the vole *Arvicola terrestris cantiana* in loess sequence *Ariendorf LD I* indicate to a post-Holsteinian age on the basis of SDQ-values compared to other localities,. The changeover of the *Arvicola terrestris cantiana* subspecies A and B occurs in subaerial units *Ariendorf LD I* and *LD II* respectively. The presence of *Coelodonta antiquitatis* in archaeological horizon 1 (*LD I*) also indicates a post-Holsteinian age.

[e] Event-stratigraphical interpretation and regional correlation

The basal gravels of the Leubsdorf terrace synthem are according to their morphological position, lithofacies associations and the dominance of pyroxenes of their heavy-mineral composition, equivalent to the Middle Rhine *mittlere Mittelterrasse* (mMT = tR8) aggradation level. The ARI-DT1 tephra is thought to be synchronous with the tephras interbedded in subaerial *Kärlich H I* subsynthem and equate to MIS 12. The Ariendorf Stage corresponds to the Kärlich I Stage: both contain Bt-type forest soils covered by volcanic layers which are attributed to the same volcanic (Rieden) eruptive phase. Tephrochronologically this took place during MIS 11 which means that it is most likely of Holsteinian age.

The overlying loess/palaeosol series in the Ariendorf section stratigraphically form the upward (late Middle and Late Pleistocene) continuation of the Kärlich section in the Middle Rhine type region. The loess-like units mark periglacial depositional events interrupted by soil formation and erosion. Their interpretation into a sequence of 4th order climatic cycles is not straightforward however, as is also pointed out by E. Turner (1997) and Boenigk and Frechen (1997). Geochronological control and relative biostratigraphical information constrain the subaerial units *LD 0*, *LD I* and *LD II*, between about 200 and 400 ka, while in this time period only two marine isotope glacial cycles (MIS 10 and MIS 8) occurred. Since the stratigraphical position of *LD I* is within a de-

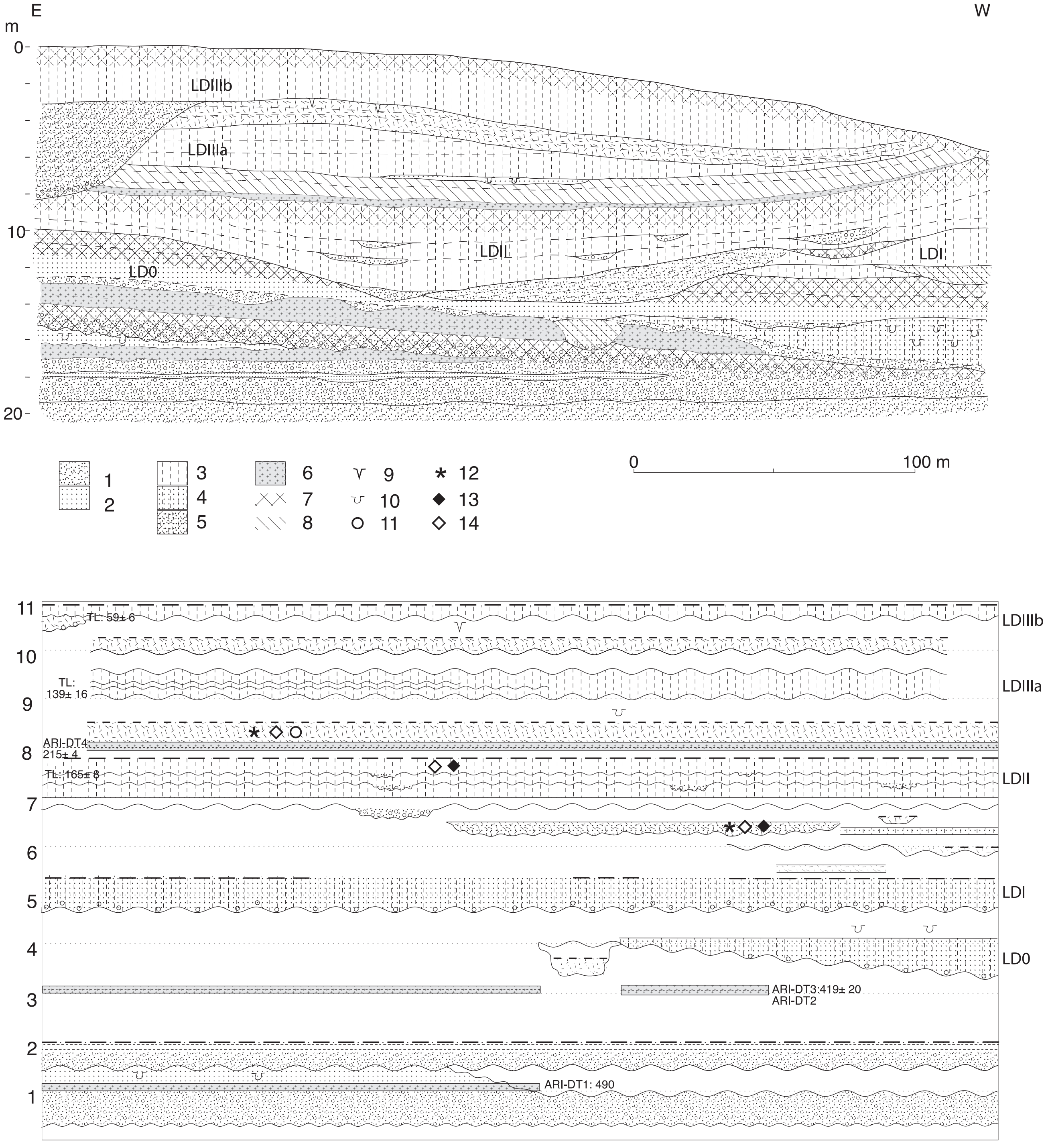


Figure 5.7: a) Lithostratigraphical model compiled from the schematic section of Ariendorf (after Haesaerts 1990; b) Interpreted chronostratigraphical model of the Kärlich section with unconformity-bounded sequence units and containing bio- and chronostratigraphical information. 1) sand and gravel/ coarse-grained lithofacies, fluvial, 2) sand/fine-grained lithofacies, fluvial, 3) silt/fine-grained lithofacies, subaerial, reworked, 4) loess/aeolian, 5) silt and fine sand / fine-grained lithofacies, subaerial, 6) silt/ fine-grained lithofacies, colluvial, soliflual, 7) tephra: b-basaltic, p-pumice, 8) leached soil (forest-Bt), 9) humic soil (Bh), 10) cryogenic structure, 11) small mammal remains, 12) large mammal remains, 13) molluscan remains, terrestrial, 14) molluscan remains, fresh water, 15) Palaeolithic finds, 16) geochronological dates.

pression, and its lithofacies composition consists of laterally changing sandy silts, it is possible that this subaerial unit does not represent a full climatic cycle. However, it consists of reworked material on which a soil has developed during a warm substage.

The correspondence of the ARI-DT4 tephra to the *Hüttenberg* pumice dated to about 215 ka implies that the soil in *LD II* cannot be assigned to the Eemian Stage but apparently corresponds to an event within MIS 7. The incorporation of the ARI-DT4 tephra in the base of the humic deposits underlying unit *LD III* and the absence of a major erosional break may indicate that its formation also coincides with a MIS 7 event. The next major basal erosional unconformity in the Ariendorf sequence is that of subaerial unit *LD IIIb* which is definitely deposited during the Weichselian Stage. The hiatus between *LD IIIa* and *LD IIIb* may be related to changeover of the Middle Terrace series to the Lower Terraces series in the Middle Rhine type area. This incision phase started at the end of the Central European loess cycle C and the equivalent Saalian glaciation cycle C. This would imply that the subaerial deposits of *LD IIIa* are of pre-Eemian age and may explain the absence of an Eemian-age soil complex.

5.2.3 The Miesenheim I section

Another section of stratigraphical importance is that of Miesenheim I, located north of Kärlich along the southern valley side of the Nette river, a tributary of the Rhine. As a consequence of commercial extraction of pumice, a sequence of subaerial deposits in a slope situation was exposed (Brunnacker *et al*. 1975, Boscheinen 1989). A review of the investigations which have taken place is given in E. Turner (2000). Although the sequence is post-depositionally dislocated by normal faulting internal structures are undisturbed. Part of the sequence (*Fig. 5.8*) is of interest because of the stratigraphical position of warm-stage deposits below volcanic beds. Overlying a fluvial sandy unit, containing pyroxenes, a sequence of colluvial deposits (fine sand and silt) and clayey marsh deposits is found. This lacustrine/mire sequence contains warm-stage fauna assemblages among which *Arvicola terrestris cantiana* (Van Kolfschoten 1988), as well as an archaeological horizon. Based by an erosional unconformity a gravel layer (basal 'lag') and a reworked subaerial unit follow upon which a fossil soil has been formed. They are unconformably covered by basaltic and pumice beds. These marker beds are compositionally equivalent to the KAE-DT 1 and KAE-BT2 tephra layers in unit *Kärlich H I*. The pumice at Miesenheim I was dated at about 460 ka by Van den Bogaard (in Turner 2000).

The succession corresponds to the upper part of unit *Kärlich G* (*i.c.*. subunit *Kärlich G V*) and to unit *Kärlich H I* except for the fossil soil which is missing in the latter unit, probably by truncation. The position of the tephra in the Miesenheim I section indicates that their deposition took place towards the end of a warm event with several short-term climatic optima. It confirms the supposition that pyroxene-rich volcanics, associated with the Rieden phase, already started during a warm climatic optimum prior to the periglacial cycle during which the aeolian deposition of unit *Kärlich H II* and the aggradation of the Leubsdorf (mMT) gravels at Ariendorf occurred. This warm event is probably equivalent to an event within MIS 13.

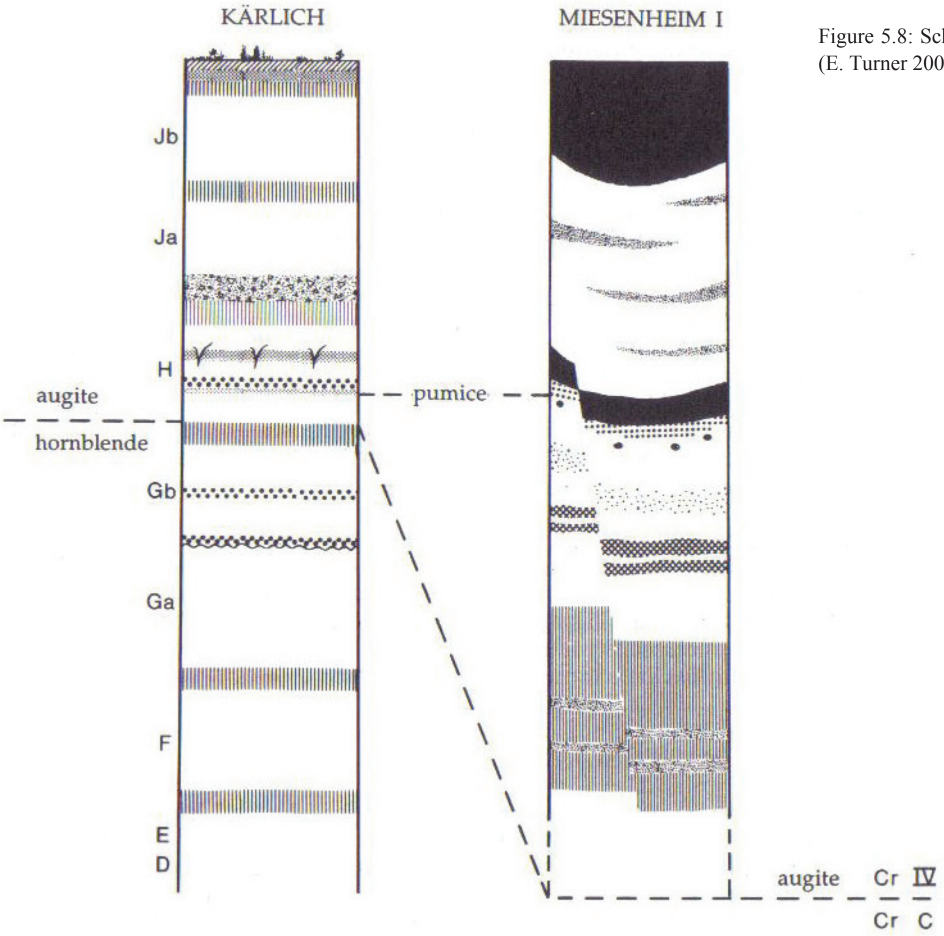


Figure 5.8: Schematic section of the Miesenheim I section (E. Turner 2000).

5.3 Correlation of the (Middle) Pleistocene depositional succession in the Middle and Lower Rhine drainage basin and the Anglo-Dutch North Sea sub-basin

The stratigraphy of the Middle Rhine type region has been discussed in *section 5.2*. The information from the well-documented key (stratigraphical) sections of Kärlich and Ariendorf is a starting point for interregional correlation of the Middle Rhine type area downstream of the river Rhine to the North Sea. This sequence can also be compared to the MIS (*section 6.4*).
First, the well-documented Pleistocene sedimentary succession and stratigraphy for the Middle Rhine, the Lower Rhine Embayment and the Anglo-Dutch North Sea basin geotectonic type areas are briefly discussed below, in terms of unconformity-bounded sequence stratigraphical units and with emphasis on the Middle Pleistocene part (*sections 5.4.1* and *5.4.2*).
Interregional (event) correlation for the three type regions is illustrated in the compiled stratigraphical scheme of *Fig. 5.9* where the units are positioned in a time frame based on the terrestrial reference records for Northwest and Central Europe (*section 4.2*). The scheme integrates all kinds of multidisciplinary evidence which have become available from the Rhineland and the Netherlands in the course of time. The objective is that these event-based correlations provide a better insight into the:

- Timing of loess/palaeosol cycles and glaciations,
- Fluvial response of the Rhine to marine transgressions/sea-level -fluctuations in the North Sea basin,
- Fluvial response of the Rhine to tectonic movements.

5.3.1 Middle Pleistocene unconformity-bounded stratigraphical framework

[a] Fluvial unconformity-bounded units in the type areas: the terrace sequence

The Middle Pleistocene succession of the Middle and Lower Rhine type areas naturally is characterised by the fluvial and deltaic accumulations supplied by the Rhine and its tributaries. They are preserved as depositional units of different lithofacies bounded by erosional unconformities both in morphological terraces and in superposition. A contemporary subdivision of the regional groups of fluvial terrace series and alluvial formations is shown in the stratigraphical table of *Fig. 5.10*.

Supplementary to the traditional local stratigraphies, summarised in *Fig. 5.9*, the sedimentary sequences within the three geotectonic type areas are distinguished as unconformity-bounded genetic sequence units (*Fig. 5.10*). Classification of units bounded by unconformities of some lateral continuity are a means of achieving a uniform and objective subdivision (*cf.* Salvador *et al.* 1994). The fluvial sequence units include information on the litho- and biofacies assemblages, gravel petrographical and mineralogical characteristics which can give further clues to their chronostratigraphical position, dating of neotectonic processes and of the climate succession. Next to the evidence from the sedimentary sequences, the abundance of bounding surfaces is of essential importance for implications on the chronostratigraphical position. The erosional surfaces that separate the sedimentary units mark considerable gaps in the geological sequence during which the river adjusted to its graded profile. In upland areas of continual uplift, such as the Middle Rhine (MR) region, this comprises downcutting to a new floodplain level, whereas in the downstream areas, the Lower Rhine Embayment (LRE) and Anglo-Dutch North Sea (AD-NS) basin, the unconformities become superimposed by subsequent aggradation as a consequence of subsidence and sea-level fluctuations. Here climatic signature is more clear since the units contain channel-fill deposits reflecting warm climate conditions.

The unconformity-bounded fluvial terrace units constitute the traditional building blocks of the Quaternary stratigraphical framework in the German Rhineland. They are grouped into the following highest level fluvial sequence groups or supersynthems, based on main unconformities and gravel -and heavy-mineral content:

- MR Lower Pleistocene Terrace (UPT: *UnterPleistozäne Terrassen*) -, MR Upper Terrace (HT: *Hauptterrassen*) -, MR Middle Terrace (MT: *Mittelterrassen*) - and MR Lower Terrace (NT: *Niederterrassen*) sequence groups.
- LRE Upper Terrace (HT) -, LRE Middle Terrace (MT) - and LRE Lower Terrace (NT) sequence groups.

The German terrace stratigraphy largely corresponds to the counterpart Dutch superimposed alluvial formations[3], based on lithology and petrography of cores. Here are distinguished:

- *AD-NS Baltic Stream* alluvial sequence group, including the Peize/Harderwijk and Appelscha/Enschede Formations of eastern provenance.
- *Lower Rhine Waalre*/Tegelen-Kedichem -, Sterksel -, Urk - and Kreftenheije alluvial sequence groups of Rhine provenance. The former group corresponds with the Tegelen and Holzweiler Formations in the LRE type area (Boenigk 2002, *Fig. 5.10*).
- *Lower Meuse Beegden*/Veghel alluvial sequence group of Meuse provenance.

Unfortunately, it is not possible to follow terraces predating the lower terraces (*Niederterrassen*) in the longitudinal profile of the lower, middle and upper Rhine sections. The different classifications of the terraces in each section are not easily compatible because of the different independent tectonic histories and interpreted climatic change. Correspondence of upstream and downstream fluvial terrace deposits, along the valley sides of the Middle Rhine section and in the Lower Rhine Embayment, and the stacked alluvial sequence in the Netherlands, is only possible on the basis of gravel and heavy-mineral analysis and of palaeomagnetic measurements (Boenigk 1995):

- The Middle Rhine and Lower Rhine Embayment Upper Terrace sequence groups (HT) and the Lower Rhine Sterksel sequence group are characterised by Rhine gravel assemblages and the absence or low percentages of volcanic minerals. For the greater part these comprise (cold-climate) coarse-grained sedimentary units which can be stratigraphically associated with the mid-Quaternary accelerated uplift phase in the Rhenish Shield from about 1.1 and 0.7 Ma (Boenigk 2002). They are also associated with a drainage course through the western part of the Lower Rhine Embayment into the Rur Valley Graben of the Anglo-Dutch North Sea basin.
- The Middle Rhine and Lower Rhine Embayment Middle Terrace sequence groups (MT) and the Lower Rhine Urk sequence group combine the Middle Pleistocene fluvial sequences of Rhine gravel assemblages which are also dominated by volcanic minerals. This main distinguishing criterion reflects the start of volcanic activity in the East Eifel region. The MT series are in the first instance dominated by brown hornblende (upper MT, MT1) and subsequently by pyroxenes (middle MT, MT2). Reworking and incorporation of local source material, however, are obscuring factors in distinguishing between simultaneously deposited Rhine sediments. As a consequence of continued uplift, they are situated at the sides of the entrenched Rhine valley, and connected with stream courses through the eastern part of

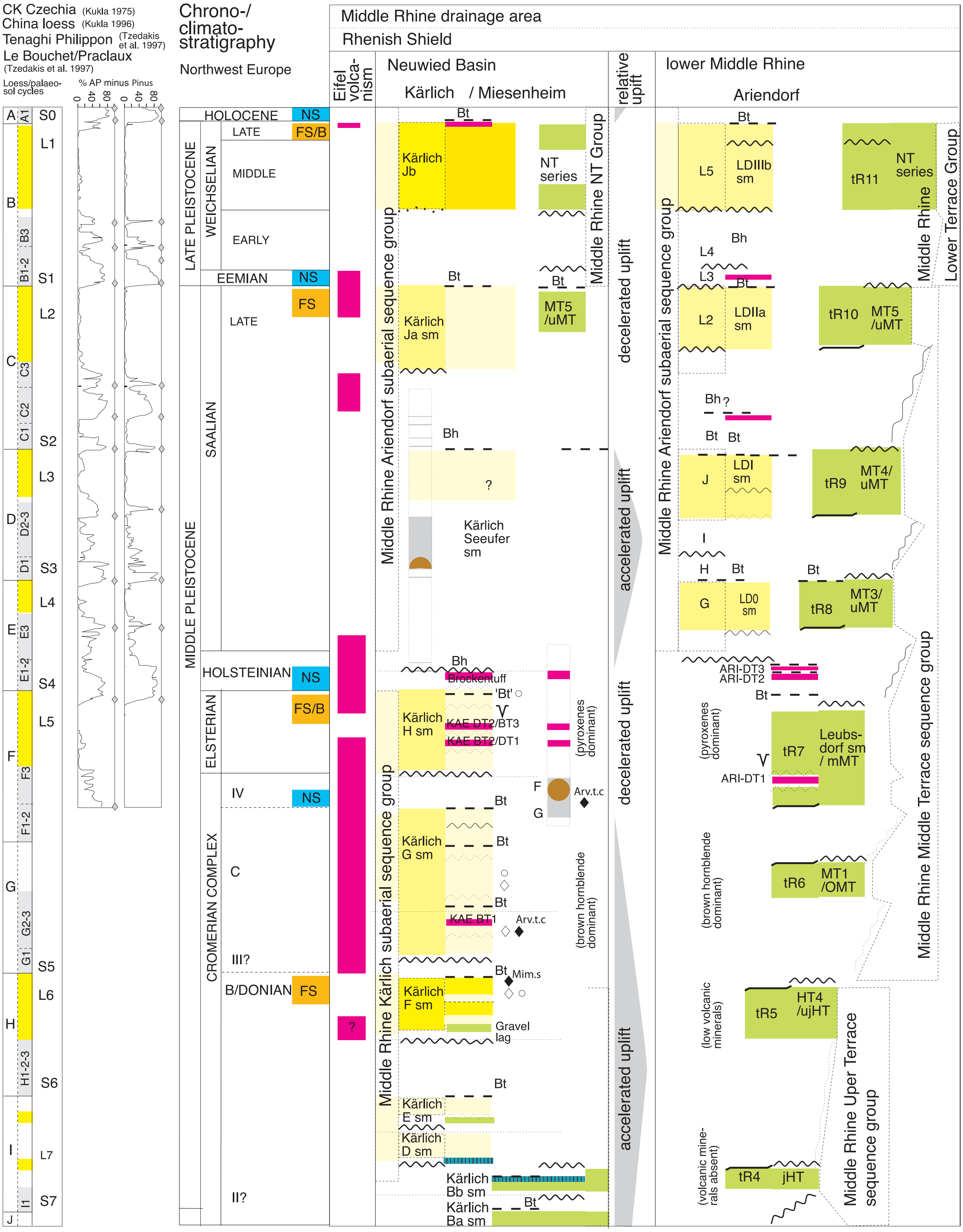
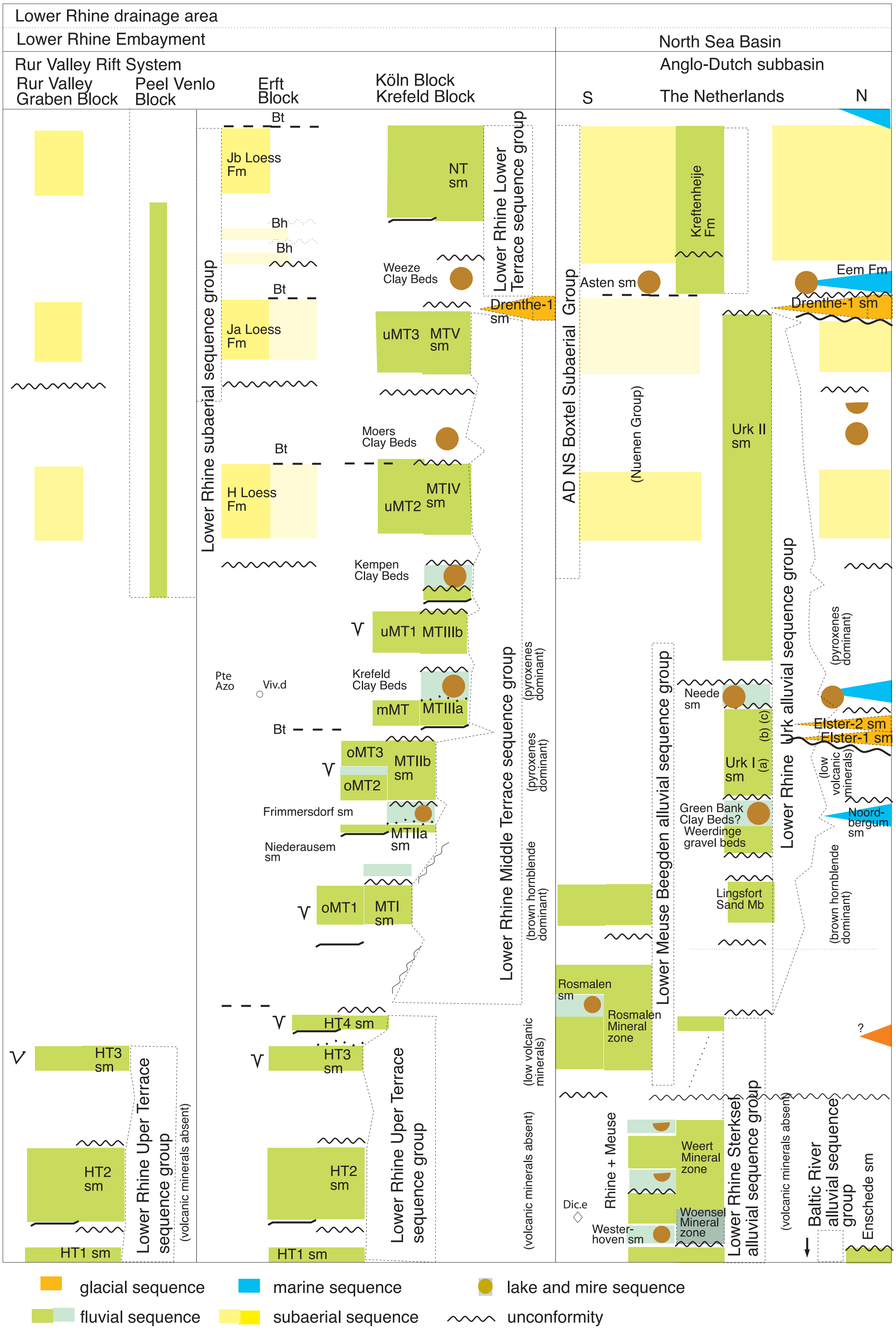


Figure 5.9: Correlation scheme of the Middle and Late Pleistocene genetic sequences for the Middle Rhine -, Lower Rhine Embayment - and Anglo-Dutch North Sea type areas. Compiled of data from Boenigk 1995, Boenigk and Frechen 2001, Brunnacker *et al.* 1969, Van den Bogaard & Schminke 1990, Schirmer 1990, Hoselmann 1994, Haesaerts 1984, Klostermann 1992, Turner 1997, 2001, Zagwijn 1974, 1989.


Lower Rhine drainage area
Lower Rhine Embayment
Rur Valley Rift System
Rur Valley Graben Block
Peel Venlo Block
Erft Block
Köln Block Krefeld Block
North Sea Basin
Anglo-Dutch subbasin
S
The Netherlands
N
Bt
Jb Loess Fm
Bh
Bh
Bt
Ja Loess Fm
Bt
H Loess Fm
NT sm
Weeze Clay Beds
Lower Rhine Lower Terrace sequence group
Drenthe-1 sm
uMT3 MTV sm
Moers Clay Beds
MTIV sm
uMT2
Kempen Clay Beds
uMT1 MTIIIb
Krefeld Clay Beds
mMT MTIIIa
Pte Azo
Viv.d
Bt
oMT3 MTIIb sm
oMT2
Frimmersdorf sm
MTIIa sm
Niederausem sm
oMT1 MTI sm
Lower Rhine subaerial sequence group
Lower Rhine Middle Terrace sequence group
(pyroxenes dominant)
(pyroxenes dominant)
(brown hornblende dominant)
(low volcanic minerals)
(volcanic minerals absent)
HT4 sm
HT3 sm
HT3 sm
HT2 sm
HT2 sm
HT1 sm
HT1 sm
Lower Rhine Uper Terrace sequence group
(volcanic minerals absent)
Lower Rhine Uper Terrace sequence group
AD NS Boxtel Subaerial Group
Asten sm
Kreftenheije Fm
(Nuenen Group)
Urk II sm
Eem Fm
Drenthe-1 sm
Neede sm
Urk I sm
(a)
(b) (c)
Elster-2 sm
Elster-1 sm
Green Bank Clay Beds?
Weerdinge gravel beds
Noord-bergum sm
Lingsfort Sand Mb
Lower Rhine Urk alluvial sequence group
(pyroxenes dominant)
(low volcanic minerals)
(brown hornblende dominant)
Lower Meuse Beegden alluvial sequence group
Rosmalen sm
Rosmalen Mineral zone
?
Rhine + Meuse
Dic.e
Weert Mineral zone
Woensel Mineral zone
Wester-hoven sm
Lower Rhine Sterksel alluvial sequence group
(volcanic minerals absent)
Baltic River alluvial sequence group
Enschede sm
glacial sequence
marine sequence
lake and mire sequence
fluvial sequence
subaerial sequence
unconformity

the Lower Rhine Embayment into the Anglo-Dutch North Sea basin. Here, they are interrupted by several glacial and marine sequences originating from the pronounced 100 ka climatic cyclicity of the last 700 ka. The latter may have had a larger impact upstream in the Rhine basin than before, resulting in distinct climatically-driven unconformity-bounded, coarse- and fine-grained units (*next section*).
- The Middle Rhine and LRE Lower Terrace sequence groups (*Niederterrassen*) and the Lower Rhine Kreftenheije sequence group refer to the Late Pleistocene fluvial sequences which are documented by Rhine gravel assemblages post-dating the penultimate Fennoscandian glaciation cycle C and preceding different, and often geochronometrically dated, Late Pleistocene and Holocene deposits.

Furthermore, volcanic mineral contents provide additional means of large- scale correlation with adjacent regional terrestrial sedimentary sequences for example with the subaerial units.

[b] Subaerial unconformity-bounded units and pedocomplexes

Aeolian and slope deposits that bury the river terrace surfaces are in a similar way as the alluvial sediments distinguished as different synthems of different ages bounded by subaerial erosional and exposure unconformities. Most loess sequences covering the terrace surfaces are found at the western lee valley side of the Rhine. They, and the dated tephra beds, provide a minimum age limit for the underlying terrace gravel units.

The following subaerial sequence groups are distinguished:
- the *Middle Rhine Kärlich* subaerial sequence group, comprising the units Kärlich D, E, F, G, H I, and the *Middle Rhine Ariendorf* subaerial sequence group, including the Ariendorf LD 0, LD I, LD II, LD IIIa, LD IIIb synthems and sequences.
- the *Lower Rhine Embayment Rheindahlen* subaerial sequence group, consisting of the Rheindahlen H, Ja and Jb synthems and sequences.
- the *AD-NS Boxtel/Eindhoven+Twente* subaerial sequence group, consisting of terrestrial silts and (fine) sands of different lithofacies (up to eight lithostratigraphical members are incorporated (Weerts *et al*. 2003, Westerhoff *et al*. 2003) which have not been further subdivided into synthems in the scheme of *Fig. 5.9*).

At a synthem level, representing one depositional cycle, units consist of at least one primary loess and/or sandy loess deposit and/or locally reworked soliflual and colluvial deposits, separated by a pedocomplex and a major erosional unconformity. Palaeosols/pedocomplexes are classified at a subsynthem level with reference to the soil type.

The oldest typical loess beds overlying the fluvial terrace sediments are from the Middle Rhine type region. They are documented at Kärlich in the Middle Rhine Neuwied basin resting on the first terrace gravels which are of normal Brunhes polarity. In many cases they are intercalated with volcanic ash and tuff deposits that occur in sheets and gully fills. Volcanic eruptions and fluvial undermining have been of importance for the deposition and reworking of the subaerial units. Incorporated volcanic minerals next to faunal evidence are a valuable stratigraphical tool for correlation.

Most distinguished subaerial units in the type regions do not comprise the typical platform loess type but show slope - or colluvial reworking features such as: a) horizons and lenses of sand and gravel, mostly at the base, b) inclining beds bounded by minor unconformities, c) wavy lamination, and d) sandy intervals (cover sands). They are indicated by light yellow colours.

5.3.2 Event-stratigraphical correlation of Middle Pleistocene sedimentary sequences and unconformities

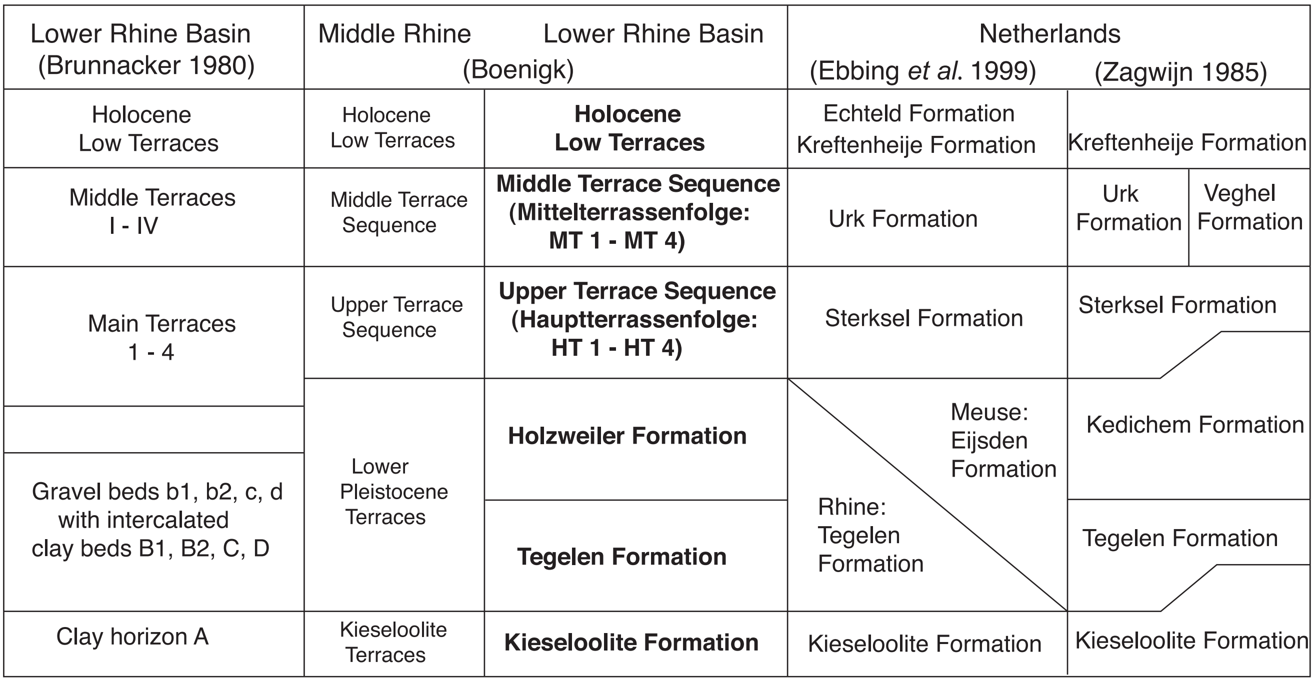
The Pleistocene cyclic processes of fluvial incision and aggradation in the different catchment segments of the river Rhine are a combined result of neotectonics, climate and sea-level change. In the midstream section (Central Rhineland) they intervene with dated volcanic activity and subaerial periglacial deposition and soil formation whereas downstream, in the Anglo-Dutch North Sea basin, they interdigitate with marine and glacial events. The chronostratigraphical framework of *Fig. 5.9* is used to provide clues for the correlation of these events.

These continual processes operated at different scales and magnitudes. Long-term (4th and lower order) differential uplift and subsidence rates along the rift system control the drainage patterns in the Rhine catchment, accommodation space for the sediments and their preservation potential.

Climatic cyclicity of the 4th and 5th order, reflecting the characteristic Middle Pleistocene 100 ka climatic cyclicity, is superimposed on the tectonic cycles. The repetitive occurrence of cold and warm stages, and precipitation variations, controls glacio-eustatic sea-level fluctuations, vegetation cover, extent of glaciations and periglacial conditions which in their turn have affected the dynamics of the regional fluvial depositional environments by changes in sediment supply, discharge and base levels of erosion.

The distribution and thickness of the preserved floodplain remnants along the valley sides of the Middle Rhine and in the Lower Rhine Embayment graben structures indicate increased sedimentation rates both as a compensation to tectonic movements and as a result of particularly cold climate conditions. Therefore, the presupposed relationship between gravel accumulation (= high sediment supply) and climatic change in the terrace stratigraphies of the Middle and Lower Rhine areas is not as straightforward as is generally thought (Boenigk 1991). The cold-stage association of the terrace gravel deposits and of the covering loess sequences, on the other hand, is undisputed. The terrace bodies in the Middle Rhine region represent predominantly early and late cold-stage aggradation phases exceeding the incision tempo in this area of continual uplift. Many terrace complexes in the Lower Rhine Embayment, however, document several more erosion and aggradation phases, represented by channel-fill deposits. They not only reflect cold-stage compensation for subsidence in the depocentres of the Lower Rhine Embayment grabens and the North Sea basin but also should be considered, and corrected, for local and regional post-sedimentary tectonics and response to glacio-isostatic effects. Therefore, age indications on climatic cycles of the lower erosion surfaces by height levelling should be undertaken carefully and only within the geotectonic type regions. Gravel and mineralogical contents, chrono- and biomarkers in the sedimentary sequences provide better means of correlation.

The morphological position of the terraces related to tectonics thus plays a minor, but higher level, role in the recognition of individual climate-driven sedimentary cycles. They corroborate the threefold subdivision into upper, middle and lower terrace sequences. The largest erosional unconformity in the type regions occurred after the aggradation of the Middle Rhine jHT, the Lower Rhine Embayment HT3 and the Lower Rhine Sterksel alluvial sequence units. It is associated with a phase of accelerated uplift (*section 5.3.1*) which is also recognised in other European type regions, e.g. in the northern and eastern Alpine forelands. Since the gravels of the jHT and HT4 show normal polarity and the start of East Eifel volcanism, which may be a cause of this tectonic event, is



Lower Rhine Basin (Brunnacker 1980)	Middle Rhine	Lower Rhine Basin	Netherlands		
	(Boenigk)		(Ebbing *et al.* 1999)	(Zagwijn 1985)	
Holocene Low Terraces	Holocene Low Terraces	**Holocene Low Terraces**	Echteld Formation Kreftenheije Formation	Kreftenheije Formation	
Middle Terraces I - IV	Middle Terrace Sequence	**Middle Terrace Sequence (Mittelterrassenfolge: MT 1 - MT 4)**	Urk Formation	Urk Formation	Veghel Formation
Main Terraces 1 - 4	Upper Terrace Sequence	**Upper Terrace Sequence (Hauptterrassenfolge: HT 1 - HT 4)**	Sterksel Formation	Sterksel Formation	
	Lower Pleistocene Terraces	**Holzweiler Formation**	Meuse: Eijsden Formation	Kedichem Formation	
Gravel beds b1, b2, c, d with intercalated clay beds B1, B2, C, D		**Tegelen Formation**	Rhine: Tegelen Formation	Tegelen Formation	
Clay horizon A	Kieseloolite Terraces	**Kieseloolite Formation**	Kieseloolite Formation	Kieseloolite Formation	

Figure 5.10: Stratigraphy of the Middle Rhine type region, the Lower Rhine Embayment and the Netherlands (Boenigk 2002).

recognised in MT1 and the Lower Rhine Urk alluvial sequence group, the beginning of this incision phase is dated between 600-800 ka (equated to MIS 16-19).

Parts of the 'cover-series' at Kärlich and Ariendorf can be correlated with the resembling Central European reference loess/palaeosol record of Červený Kopec (Kukla 1977). Because both sequences are located in tectonically active upland areas with generally more humid climates than eastward, straightforward recognition of glacial-interglacial cyclicity, as in the Russian and Chinese terrestrial records, is more complicated. Nevertheless, units Kärlich D, E, F and H represent depositional cycles containing basal wash, silty beds with structures and a Bt of a para-brownearth soil. Unit Kärlich F contains genuine loess and coincides with CE loess cycle H and China loess cycle L6. Correlation is based on the absence of volcanic minerals, the presence of *Mimomys savini* and the *Pupilla* molluscan fauna. This evidence also points to correspondence to an event within MIS 16.

The pronounced soils of unit Kärlich G are most likely correlative with the red forest soils in CE cycle F. They also may correspond to the Ferreto soils and Riesenboden in the northern Alpine Foreland that indicate a warm savannah-type climate. Moreover, there are no extreme cold climate conditions indicated in unit Kärlich G which is consistent with the loess records in Central Europe and Eurasia. The overlying unit Kärlich H then may correspond to the loess deposition of CE cycle F. The dating of the tephra layers at about 450 ka then equates unit Kärlich G with MIS 15-13 and unit Kärlich H with MIS 12.

Channel-fill sequences in the Lower Rhine Embayment Middle Terrace sequence units MT2 and MT3 are palynologically pre-Holsteinian and coincide with warm events also represented in unit Kärlich G (equated to MIS 15-13).

The glacial sequences of the Elsterian glaciation traditionally separate the Middle Pleistocene in Northwest Europe into early and late Middle Pleistocene parts. The correlation of these glacial sequences from the Netherlands to the upstream Middle Rhine terrace and loess stratigraphy is crucial in the reconstruction of an interregional chronostratigraphical framework. From the scheme compiled in *Fig. 5.9*, it is plausible that the Elsterian glacial event is time equivalent to the Lower Rhine Embayment MT2 - and Middle Rhine mMT aggradation levels. Both these units are rich in pyroxenes and the latter is intercalated by a tephra stratum dated to about 490 ka. The Elsterian glacial sequence in the North Sea basin interdigitates with pyroxene-rich parts of the Lower Rhine Urk alluvial sequence group. Since their dispersal has already been recognised in a warm climatic optimum, prior to the deposition of unit Kärlich H, also identified in the Miesenheim I section, the Elsterian glacial cycle H probably relates to MIS 12.

The above conclusions imply that the North Sea Holsteinian marine transgression and local contemporaneous forest climaxes, of which the sedimentary sequences directly overlie the Elsterian glacial sequence should therefore be equated with an event within MIS 11. The Holsteinian marine transgression reached the northern Netherlands, e.g. at Noordbergum (Zagwijn 1973). It is, however, not dated by pollen in the type areas, contrary to the numerous evidence from glacial lake records in other type regions. There is little evidence for equivalents of the Holsteinian forest vegetation in the Rhine fluvial succession. Only the Krefeld clay beds meet the palynological criteria and also contain the freshwater mollusc *Viviparus diluvianus* that characterises the fluvial Holsteinian environments in Northwest Europe. The clay beds are deposited in a channel fill cut into the Lower Rhine Embayment MT2 terrace synthem.

5.4 Late Middle Pleistocene stratigraphy of the Subhercynic basin type region: the sections at Schöningen

The Subhercynic basin type region is located in the Central German uplands, north of the Harz mountains (northern Harz foreland) (*Fig. 4.1*). Together with the adjoining Thuringian basin type region, it is of Mesozoic origin. Triassic and Jurassic rocks dominate the geology while Tertiary and Pleistocene strata predominantly occur in salt tectonic-related basins and valleys. Diapiric rock-salt intrusions still are active in the area. The Pleistocene stratigraphy in both type regions is based on:

- The interaction of glacial sediments and local lake and mire sequences.
- The fluvial terrace sequences of the northward rivers belonging to the Elbe and (partly) to the Aller/Weser catchment areas.
- Loess/palaeosol sequences covering the terraces.
- Local-scale travertine deposits.

The Subhercynic Basin type area has been glaciated twice during the Middle Pleistocene. The ice-sheet advances of the Saalian and Elsterian glaciations left thick sedimentary sequences. In the former ice-marginal zones they interfinger with and separate the fluvial sequences of the middle course section of the river Elbe and its tributaries. Fluvial deposits intermediate between both glacial sequenes are joined in the *Mittelterrassen Komplex*. In the southernmost non-glaciated parts of the Thuringian Basin gravel terrace series occur which are overlain by loess/palaeosol deposits. The occurrence of travertine sheets in the terraces is associated with seepage of calcareous groundwater along faults. The location and origin of many former lakes is predominantly related to local subsidence due to subrosion[4] of the rock salt diapirs. The lacustrine sequences are rich in fossils which are generally well preserved, also because of the calcareous groundwater.

5.4.1 The Schöningen sections

[a] Geotectonic setting and stratigraphy

The open-cast lignite mines in eastern Lower Saxony, near the towns of Helmstedt and Schöningen, are located in the elongate rim synclines on either side of the Beiersrode-Helmstedt-Staßfurt salt structure (*Fig. 5.11*). They lie between the structural features of the Elm salt pillow and the Lappwald block. The NW-SE trending rim synclines are filled in with Palaeogene parallel-bedded lignite strata intercalating with laminated fine sand, silt and clay layers of marine origin. The brown coal beds have been exploited for many decades. The progressing excavations also gave good opportunities to study the overlying Pleistocene sediments over 100's of metres. The Pleistocene sequence rests unconformibly on

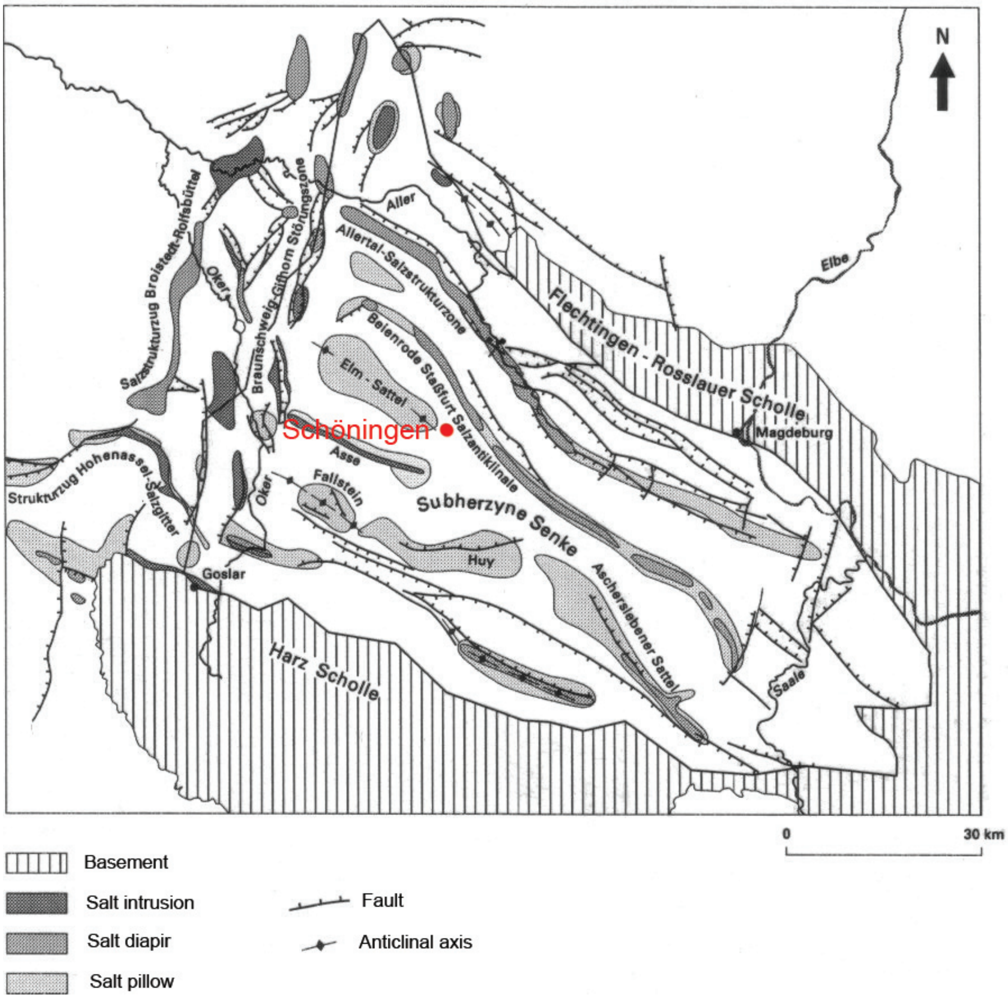


Figure 5.11: Location map of the Schöningen sections in the Subhercynic basin.

the Tertiary strata. The erosional base is polygenetic and heterochronous. The Pleistocene sediments have a maximum thickness of 45 m in a north-south orientated incised valley, along the axis of the syncline.

Multidisciplinary geological and archaeological investigations in the open- cast excavations have been carried out since 1983, mainly by the research team of Dr. Thieme (Landesamt für Denkmalpflege, Hannover). These have resulted in numerous publications. The earliest reports (Urban *et al*. 1988, Urban *et al*. 1991a, Urban *et al*. 1991b) concern the now closed northern part of the Schöningen mine (Baufeld Esbeck). From 1991 only one open-cast mine remained in operation in the western rim syncline, Baufeld Schöningen-Süd. Data and results from the investigations of the here exposed sections have been reported by Thieme and Mania (1993), Thieme *et al*. (1993), Thieme and Maier (1995), Urban (1995) and Thieme (1996).

A geological cross-section from this part of the western rim syncline is shown in *Figure 5.12*. The following lithogenetic stratigraphical units can be distinguished in the Schöningen outcrops (*Fig. 5.12* and *Fig 5.13*):

- Sediments generated in glacial environments.
- Non-glacial sediments of subaerial periglacial aeolian origin (loess and loess derivates) and subaerial periglacial reworked slope deposits.
- Non-glacial sediments of lacustrine origin and mires.
- Fluvial sediments of local origin.
- Secondary carbonates.

[b] Glacial depositional sequence units and unconformities

Two glacial sequences can be distinguished in the Schöningen area and its surroundings: a lowermost glacial sequence of Elsterian age, and a Saalian-age glacial sequence. Ice lobes at the margins of both ice-sheets invaded the lower and middle sections of the then Elbe and Aller/Weser catchment areas from the north. Their advances blocked the drainage in the German upland areas and this was accompanied by deposition of large volumes of sediment in temporary ice-marginal lakes. The Elsterian glacial sequence, comprising the oldest Pleistocene sediments in the open-cast mines, reaches a maximum thickness of 25 m. The sediments were laid down in a proglacial channel draining meltwater towards the south-southwest into the Großes Bruch. This in turn joined a westward draining ice-marginal meltwater system. The palaeochannel left the rim syncline just south of the town of Schöningen. It is infilled by proglacial depositional sequences during the ice-sheet expansion phase: glaciofluvial sand and gravel ('*Vorschuttsande*') at the base, followed by (non-calcareous) glaciolacustrine clay, silt and fine sand. Sand and gravel beds within the sequence contain many reworked Tertiary components. They are overlain by till beds deposited during subsequent glacial overriding. Two Elsterian till units are reported from the northern part of the Schöningen mine. Glaciotectonic structures also are found. Glaciofluvial sand and gravel units ('*Nachschuttsande*') follow, which were deposited during deglacial ice marginal conditions.

The uppermost Saalian glacial sequence has a maximum thickness of 10 m and shows a similar dynamic sedimentary environment. The proglacial sand and gravel units, above the erosional base, attain a general thickness of about 2-3 m and are intercalated with silt lenses. Till beds, mostly decalcified, are up to 3 m thick and contain many glaciofluvial sand and gravel units. Glaciotectonic structures, reported by Lütge (1984) from the former Alverstorf open-cast mine, are also found in the southern part of the Schöningen mine (Bartholomäus & Elsner 1995). They comprise folded and upthrusted Tertiary lumps that interdigitate with glaciofluvial deposits.

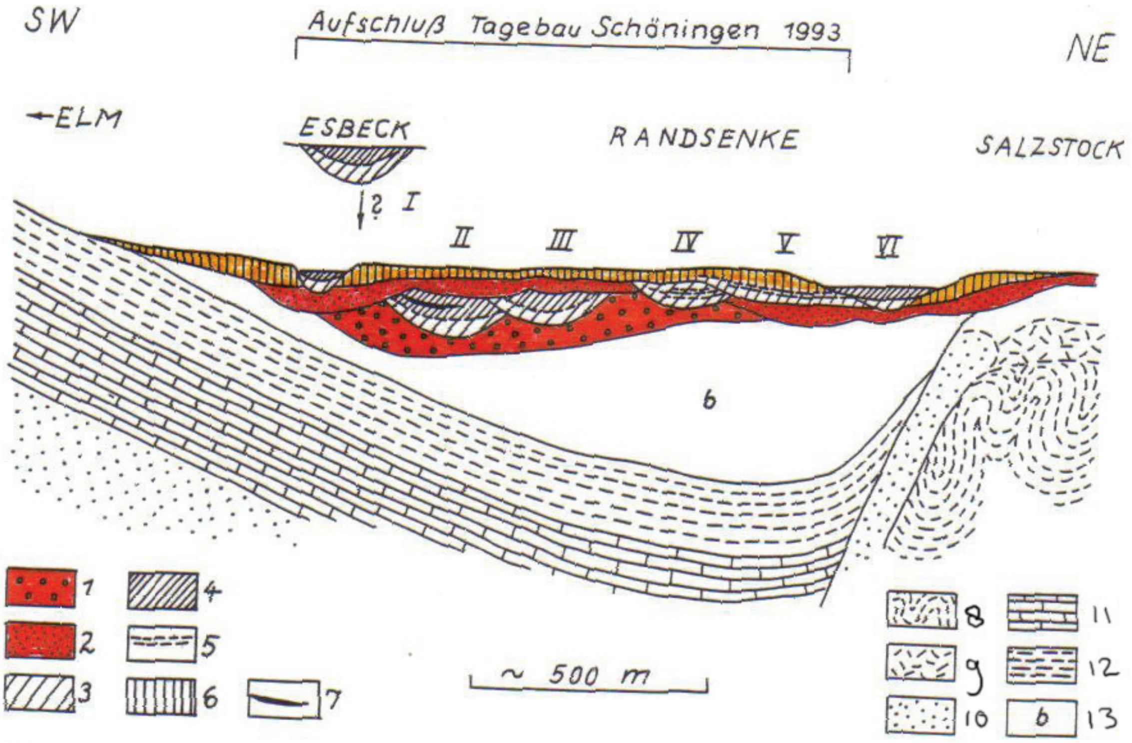


Figure 5.12: Schematic geological cross-section of the Schöningen open-cast mine in the western part of the rim syncline of the Beiersrode-Helmstedt-Staßfurt salt structure (Mania 1993). 1. Elsterian glacial sequence, 2. Saalian glacial sequence, 3. subaerial sequence, 4. lake and mire sequence, 5. soil complexes, 6. subaerial (loess) sequence, 7. Palaeolithic horizon, 8. Zechstein rock salt, 9. cap rock, 10. Buntsandstein , 11. Muschelkalk, 12. Keuper, 13. Tertiary.

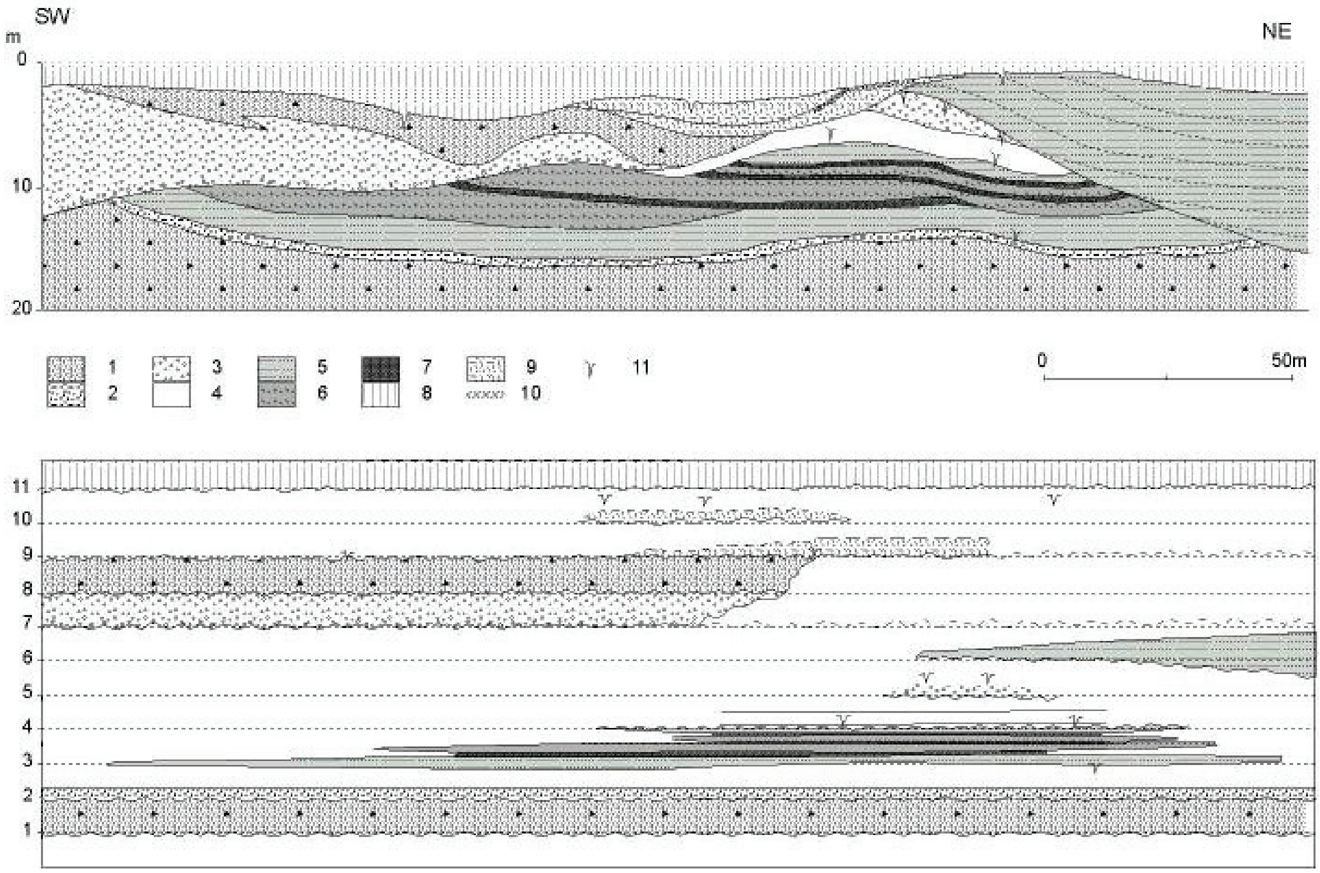


Figure 5.13: a) Lithostratigraphical and b) chronostratigraphical models based on schematic SW-NE section of Schöningen 12B by Thieme *et al.* 1993. 1. till, 2. gravel, 3. sand and gravel, 4. sand, 5. fine sand and silt, 6. clayey silt and mud (lake marl), gyttja, 7. peat, 8. loess, 9. loess derivates ('Fließerde', 'Fließlöss').

[c] Intermediate non-glacial depositional sequence units and unconformities

The preserved non-glacial deposits intermediate of the Elsterian and Saalian glacial sequences comprise fine-grained lithofacies assemblages which are found in broad, laterally superimposed gulleys ('*Rinnen*') and depressions. During the ongoing excavations several of these NE-SW trending lows have been identified in the Schöningen rim syncline, both in the northern and southern part of the mine. Following detailed investigations from the southern mine field, Thieme and Mania (1993) reconstructed a series of three laterally superimposed 'climato-cyclic' depositional sequences preceding the Saalian glaciation. Their geometry is summarised in a cross-section (*Fig. 5.12*) showing the three unconformity-bounded gully fill sequences shifting laterally in an easterly direction, towards the salt diapir. Each climatic cycle is represented by sand and gravel at its erosional base, followed by low angle bedded fine sand and silt units (loess derivates, '*Beckenschluffe*' and '*-löss*', often laminated) which are overlain by lake muds and silts alternating with limnic/telmatic peat layers[5]. The fine sand and silt units are of allochtonous origin and comprise subaerial aeolian sediments, generally reworked by slope wash and solifluction, deposited in periglacial environments. In contrast, the lake and mire sequences, rich in fossils, reveal changing open-water hydrological conditions during warm-stage periods. The sections are biostratigraphically distinguished by pollen analyses and macro- and microfaunal evidence from the lake and mire sequences. Initially two warm forest intervals were identified by Urban *et al.* (1988, 1991b) from exposures in the northern opencast mine (Baufeld Esbeck). Deposits of the oldest cycle, cycle I: equivalent to Esbeck (*Fig. 5.12*), were found in a gully infilled with a 14 m thick hydrosere succession of clay and silt containing molluscs and plant remains and several peaty layers. The sequence is assigned to the Holsteinian Stage on the basis of its stratigraphical position, characteristic forest vegetation assemblage and the occurrence of *Pterocarya* (Urban *et al.* 1991b). Unfortunately, only a lithological column of this limnic-telmatic gully fill is shown in their paper; its stratigraphical position in the section remains unclear. The cycle I depositional sequence is cut by a multicyclic broad gully infilled by laterally changing sand and silt sheets. These are overlain by a ca. 3 m thick calcareous, humic clayey silt in which a peat layer of more than 1 m is interbedded. The upper part of the gully is infilled by glaciofluvial sand and gravel and a till bed of Saalian age. A final sedimentary cycle in this gully sequence is formed by an Eemian channel infill of organic and travertine deposits. Two cross-sections were drawn from the exposures of this gully sequence unconformably overlying the Elsterian deposits. The sequence beds in one of the cross-sections resemble lateral increments following the easterly shifting deposition centre. From the pollen contents of the pre-Saalian organic

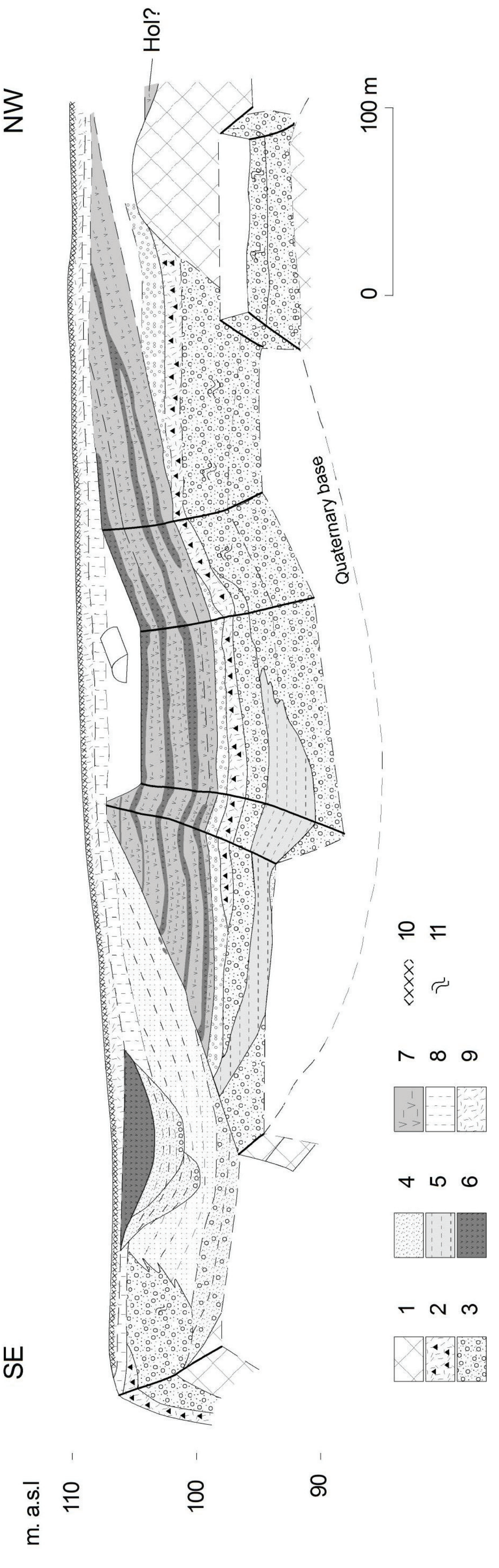


Figure 5.14: Schematic overview of the SE-NW section of Schöningen 13. 1. Tertiary clay, 2.till, 3. sand and gravel, 4. fine sand and silt, 5. fine sand and silt (glaciolacustrine), 6. peat, 7. clayey silt and mud (lake marl), gyttja, 8. loess, 9. loess derivates, 10. soil complex, 11. deformation structures.

and clayey silt beds in the section profiles, Urban *et al.* (1991) compiled a palaeoclimatic sequence in which several forested events are distinguished. They comprise the Schöningen warm event, characterised by deciduous forests and the presence of *Azolla filiculoides*, and several boreal forest periods pre- and succeeding this warm period. In spite of the occurrence of some *Pterocarya* pollen in one of the sampled profiles, the Schöningen warm event has been interpreted as being of post-Holsteinian age.

In the southern part of the mine, two 'climato-cyclic' depositional sequences are clearly exposed intermediate between the glacial sequences. They comprise the cycles II (Reinsdorf) and III (Schöningen) in *Figure 5.12*. Deposits of the Holsteinian-assigned cycle I were probably exposed for some time in a small gully infill in the northwestern edge of the Schöningen-Süd Baufeld quarry (*Fig. 5.14*). Unfortunately, no record from the organic beds in this sequence has been published yet.

The lake and mire sequence of Reinsdorf, in cycle II, is well documented. It differs on biostratigraphical grounds from the evidence found in the sequences in the northern mine part and has a stratigraphical position intermediate between them. Two schematic lithostratigraphical sections are shown: Schöningen 12B (*Fig. 5.13a*, Thieme and Mania 1993) and Schöningen 13 (*Fig. 5.14*). As an example a chronostratigraphical model has been compiled from the former section (*Fig. 5.13b*), where the different genetically-related synthems are placed in a relative time frame of depositional and erosional phases. The lower boundary of the Reinsdorf sequence shows a concave bowl-shaped unconformity of a broad depression. It is underlain by gravels of which the upper part at some places is reddened, reflecting soil processes and a hiatal break. The lower part consists of up to 3-4 m fine sand and silt, followed by several beds of limnic-telmatic deposits comprising a series of topogenous hydroseres. These fine-grained sediments of silt, mud and gyttja facies, rich in fauna, were deposited in former lakes. Peat was formed when lake levels fell or when vegetation became better established to overgrow the lake. The Reinsdorf hydrosere series in all comprises 5 phases of lake rise and fall. Whereas in the Schöningen 12B section (*Fig. 5.13*) only the first three phases are preserved, all five successive phases from open-water to mire conditions are exposed at the Schöningen 13 site (*Fig. 5.14*).

All of these levels yielded macro- and micromammal remains (Van Kolfschoten 1993), palynological assemblages (Urban 1993, 1995) and Mollusca (Mania 1993). Palaeolithic material was found just above the first phase and in the 4th phase (Thieme 1996). The most remarkable find was the recovery of the famous wooden spear in 1996 from a Palaeolithic horizon at site Schöningen 13 in the 4th level.

The limnic-telmatic series contain pollen and spores of deciduous forest vegetation. They are of late-temperate (mixed oak forest) type and contain *Azolla filiculoides*, *Abies* and *Celtis* as indicator species. Some *Pterocarya* pollen were also determined in phase 3 of the Schöningen 12b section (Thieme *et al.* 1993), which imply an Holsteinian age. Nevertheless, this was provisionally excluded by Urban (1995) who instead proposed the Reinsdorf warm phase for this sequence because of the otherwise different vegetation development, compared to the Holsteinian spectra. Its fauna assemblage contains among others *Trogonterium cuvieri* and *Arvicola* *terrestris cantiana* which are characteristic biomarkers for Holsteinian and post-Holsteinian warm events. The low SDQ-values of the vole molars indicate a subspecies B type from which a post-Holsteinian age can be assumed (Van Kolfschoten pers. comm.). The molluscan assemblages include *Helicigona banatica* which are in general typical for Middle Pleistocene sequences (Thieme and Mania 1993).

From the third glacial-interglacial depositional cycle, Schöningen cycle III (Thieme and Mania 1993), neither detailed lithological sections nor biostratigraphical data are available. Although sections were drawn from an excavated sequence by Dr. Mania, they have never been published. As can be seen in the SE-NW section of *Figure 5.14*, the Reinsdorf sequence of the Schöningen 13 site is laterally cut by a 150 m broad gully at its southern side that is largely infilled with sand and silt units (*Fließerde*, *Beckenschluffe*). This infill probably forms the lower 'cold' part of 'climato-cyclic' sequence III. The subaerial gully fill is cut by another 40 m broad channel where, above a sandy basal part, dark laminated silts and organic mud, containing plant remains and mollusc shells, occur. The stratigraphical position of this warm-stage deposits, whether cycle III (Schöningen) or cycle IV (=post-Saalian), is not clear. Saalian glacial deposits are outcropping in the southwestern edge but the interaction between the sedimentary units was badly exposed during the fieldwork. Whatever its assignment, both the Reinsdorf and these younger depositional cycles are covered by a subaerial loess sequence representing the Weichselian Stage and capped by a soil complex of the (present) Holocene Series. The evidence for the Schöningen warm event so far still comes from the northern Esbeck Baufeld mine as described by Urban *et al.* (1991a).

[d] Event-stratigraphical interpretation

While both glacial and the uppermost subaerial loess sequence units in the western rim syncline at Schöningen can undoubtely be related to large-scale Middle and Late Pleistocene glaciation events, the nature and development of the different non-glacial sequence units, intermediate between the Elsterian and Saalian glaciations, do not allow such a straightforward event correlation. They were formed in a local depositional subenvironment that, due to its unique geotectonic and geohydrological situation, related to salt tectonics, differ from those in the surrounding areas. Whereas the post-Elsterian glacial lakes in the Northwest European lowlands areas became silted up by relief levelling, repeated aggradation and incision phases at Schöningen have resulted in a series of laterally superimposed infilled gulleys and depressions.
The salt structure and basins on both sides are situated at the water divide between the Weser/Aller and Elbe drainage basins. The western Schöningen syncline basin has a small catchment and is fed by rain and springwater at the foot slope of the Elm ridge (*Fig. 5.11*). Drainage of the depression is towards the south, via the Missaue to the Großes Bruch, then eastwards in the rivers Bode and Saale, tributaries of the river Elbe. Just north of the present excavations drainage is towards the north, via the Schunter to the river Aller.

Following the Elsterian deglaciation, the area became exposed to subaerial processes. The post-Elsterian relief was in the first instance drained by a stream flowing within a gully-like ('*Rinnenartig*') form of up to 300 m broad and 15-30 m deep. The isolated geohydrological location of the rim syncline hampered discharge of surface water which might be enforced by differential subsidence rates. Parts within the elongated basin then became periodically waterlogged, whereas variation of precipitation may have caused lake levels to change. Since the lake sequences at Schöningen contain late-temperate pollen assemblages this occurred in the later parts of warm periods. Erosional and denudational processes exceeded sedimentation and subsidence at the transition of warm to cold intervals. Re-incision of broad shallow gulleys occurred by solifluction and backward erosion in the upper section of the Elbe river system. This is followed by infilling (local relief levelling) of allochtonous aeolian sediment during cold periods and at the transition to warm periods. Waterlogging may occur again in warm period optima. The genesis of the subaerial and limnic-telmatic sequence units within the gully systems may be explained in this way. This also explains the presence of short-term climatic oscillations in the palaeoclimatic reconstruction of the Schöningen sections, as reflected in the different organic beds containing boreal palynofloras that have been preserved.

5.4.2 Interregional correlation of the late Middle Pleistocene sedimentary sequences and unconformities

The outcrops at Schöningen are of interest for the late Middle Pleistocene stratigraphy. Because of the particular local depositional environment the Reinsdorf and Schöningen lake sequences have few equivalents. Interregional correlation (*Fig. 5.15*) of the warm-period lake and mire sequences at Schöningen therefore is of importance in order to demonstrate the number and timing of warm events intermediate between the Saalian and Elsterian glaciations.

Although the sequence is not in superposition, the litho- and biostratigraphical evidence point to three separate (4th order) warm-period sequences occurring in the Schöningen sections. Furthermore, several short-term climatic oscillations have been identified. Based on this evidence, Urban (1995) revised her earlier palaeoclimatic reconstructions and introduced the Reinsdorf warm Substage succeeding the Holsteinian Stage. Although evidence of the Reinsdorf event is missing in her earlier palaeoclimatic sequence, it may be equivalent to one of the boreal forest assemblages ('*Mischaue*'?) identified in the post-Holsteinian multicyclic gully sequence in the northern part of the Schöningen mine. Ten kilometres east of Schöningen, at Ummendorf, lake sequences are found in solution depressions intermediate between glacial deposits. Pollen analyses are available from three organic beds in the lacustrine sequence above Elsterian till (Strahl 1999). The lowermost and middle one contain *Pterocarya* pollen and *Azolla filiculoides*, while the uppermost bed of the sequence, separated by an unconformity, lacks *Pterocarya* pollen. These results confirm the occurrence of at least one warm event postdating the Holsteinian Stage in the area.
Because of their location and origin the lake and mire sequences in the cycles II and III are not necessarily associated with a climatic optimum following a glaciation, *i.c.* the Holsteinian Stage. The Reinsdorf pollen diagrams show late - and post temperate palynofloras, whereas the Pritzwalk (Erd 1970), Wacken (Menke 1968) and other glacial lake sequences only show early temperate phases of a post-Holsteinian warm event. Reinsdorf may reflect the late temperate phase, that is missing from these lake sequences.

Correlation of the Reinsdorf sequence with the fluvial terrace-travertine sequence of Bilzingsleben (Mania 1993) in the Thuringian Basin type area point to a correlation with sequence II, the second travertine-containing terrace level post-dating the Elsterian glacial sequence in this area. The travertine contains *Celtis* pollen and indicator faunal remains of *Arvicola terrestris cantiana* and *Trogonterium cuvieri*. In the sandy fluvial deposits of the Bilz-

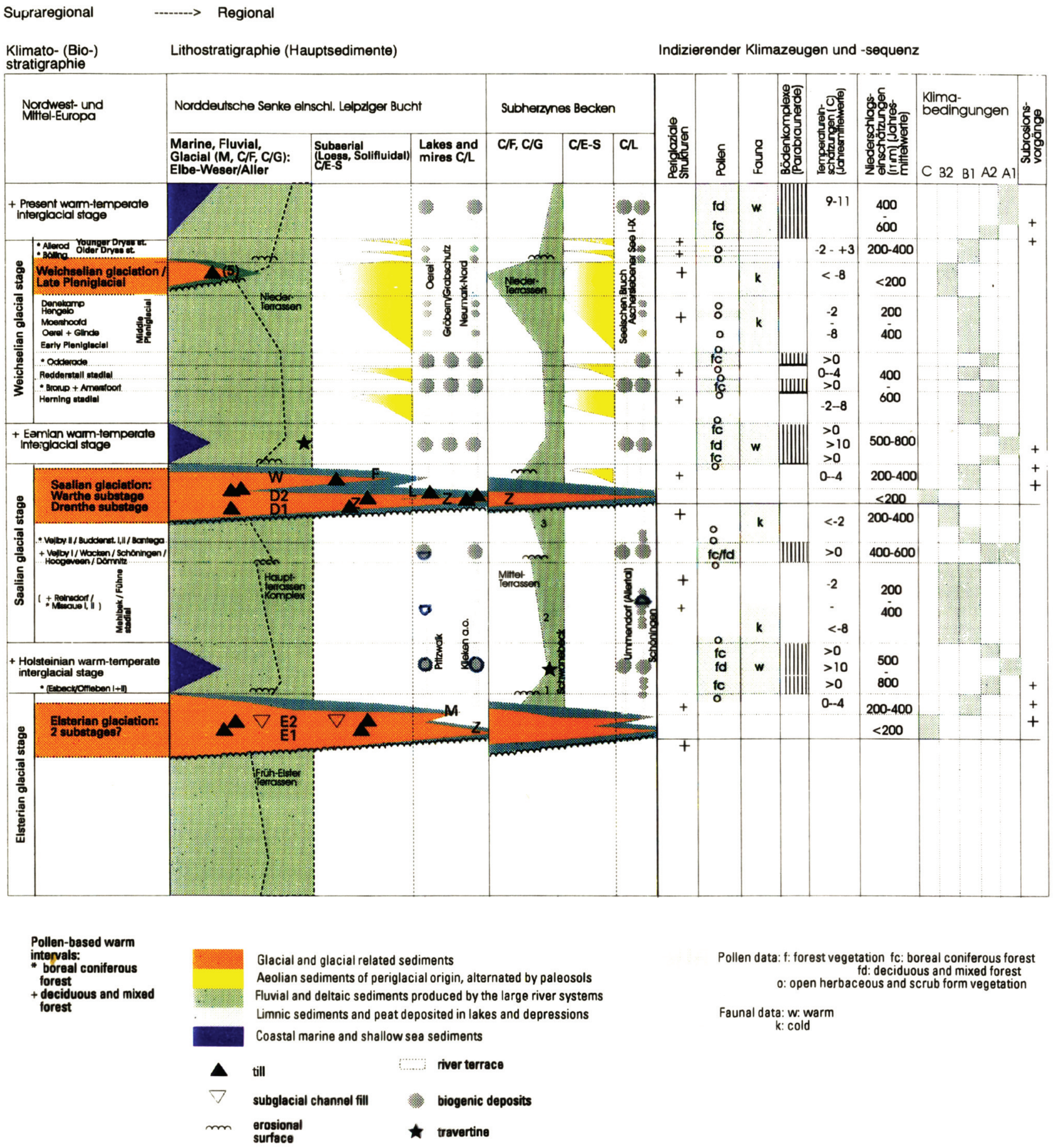


Figure 5.15: Stratigraphical correlation scheme of the late Middle and Late Pleistocene for the Subhercynic Basin and the southern part of the North German North Sea subbasin.

ingsleben II terrace synthem *Corbicula fluminalis* is present. As can be seen from *Figure 4.10* the latter two index fossils are indicative for the Holsteinian warm Stage and the warm substage following the Holsteinian. As from the Reinsdorf sequence, also Palaeolithic material has been recovered from the travertine in this terrace level. Dates from the travertine gave ages of 320-350 ka (U/Th) and 282-414 ka (ESR) (Schwarz *et al.* 1988) which most likely correspond to MIS 9.

The pollen evidence from the Reinsdorf sequence may be equivalent to the Middle Rhine Kärlich-Seeufer pollen assemblage zones (*section 5.2*). They are of post-Holsteinian age (*Fig. 4.6*) on the basis of their stratigraphical position and because they lack *Pterocarya* pollen. The results from SDQ-values of *Arvicola terrestris* molars from the Reinsdorf sequence also point to a post-Holsteinian age (Van Kolfschoten unpublished). Their higher SDQ-values, compared to Belvédère, for example, indicate an assemblage older than the third intra-Elsterian-Saalian warm event: the Schöningen Substage in cycle III. The dating of peat from the Schöningen lake sequence by U/Th-dates to about 200 ka (Heijnis 1992) confirms this assignment. Finally, correlation of the Reinsdorf warm Substage is also possible with the Lac du Bouchet Landos event, which is equated to MIS 9.

[1] *Erosional (rejuvenation) and aggradational cycles*

[2] *Such a scheme is comparable to the chronostratigraphical models or so-called Wheeler diagrams (introduced by Wheeler 1958) that are reconstructed in order to show the time relationships between the depositional systems and the erosional and non-depositional surfaces identified in the geological section.*

[3] *Because of the recently revised Dutch stratigraphy (Weerts et al. 2003, Westerhoff et al. 2003) both new and traditionally used terms are given, although the included fluvial deposits are not always equivalent.*

[4] *Underground dissolution.*

[5] *Such successions from open water to mire or bog, in which sediments gradually change in character from muds to peats, are generally known as hydroseres.*

Chapter 6

SYNTHESIS: EVENT CORRELATION OF THE MIDDLE PLEISTOCENE TERRESTRIAL SUCCESSION WITH THE MARINE ISOTOPE STRATIGRAPHY

6.1 Scope of the marine isotope stratigraphy

In the previous chapters the multidisciplinary evidence from Northwest and Central Europe has been reviewed and grouped into unconformity-bounded lithogenetic units for natural geotectonic type regions. Palaeoclimatic and tectonic events at different spatial and temporal scale order, interpreted from regional markers and climate-indicators, are provisionally put into a continent-wide framework. Now the possibilities for the refinement of the low-resolution Middle Pleistocene terrestrial stratigraphy are sought by comparison and matching with the global marine isotope stratigraphy.

With the establishment of the marine isotope stratigraphy from the long continuous oceanic sequences and the polar ice cores, Quaternary stratigraphers have once more become aware of the incompleteness and heterogeneity of the local and regional land-based stratigraphies[1]. The fragmentary depositional records do not by far approximate to the long continuous and orbitally tuned record of climate history from the marine sequence. Local exceptions are some lake and mire sequences, that have yielded detailed pollen records, although hardly ever exceeding 100 ka. Of considerable chronostratigraphical potential, but not recording continuous deposition, are the wide-spread stacked loess-palaeosol sequences in Eurasia and China spanning many climatic cycles.

The isotope stratigraphy of alternating stages of relatively high and relatively low $^{18}O/^{16}O$-ratios is related to the former composition of sea water and indicative for the global ice volume stored on land (*cf.* Shackleton and Opdyke 1973). Therefore, the climatic variability shown in the marine isotope record, in the first instance, is a guide in further constraining the timing of the major glaciations in the northern hemisphere, their associated periglacial loess deserts and glacioeustatic sea-level fluctuations. Besides, the isotope record of the oceans (and ice cores) also serves as a global-scale climate proxy which can be used as a template for reconstructing Quaternary latitudinal climate zonations from non-glacial continental depositional sequences. Using the oceanic record as a relative time reference and stratigraphical tool for interregional correlation of palaeoclimatic events for Northwest and Central Europe should however be cautiously regarded.

Unfortunately, the oceanic record can only be indirectly correlated with the Middle Pleistocene terrestrial stratigraphy mainly because of the lack of chronological controls and marker horizons. Strictly speaking only comparison of interpreted palaeoclimatic event-stratigraphical units is feasible. To what extent these diverse local- and regional-scale terrestrial climatic signatures correspond to the MIS and their informal boundary levels, discussed in *section 2.4.3*, needs to be discussed. The evidence for repeated large-scale ice-sheet expansions, periglacial loess cycles and high sea-level stands support the assumptions made in *chapter 2* that large-scale climatic change, as can be indirectly observed in the marine isotope record, is a global phenomenon. Extreme palaeoclimatic events are reflected in both global and local records. Moreover, the close correspondence of local continuous lacustrine (pollen) records to the oceanic record shows the potential of the latter as a basis for a worldwide correlation of the Quaternary succession. This supports the use of the oceanic oxygen isotope record in the next sections as a reference frame to define an improved sequence of semi-synchronous geological and biological events for the Middle Pleistocene in response to zonal climate fluctuations on the European continent. Global matching is done at two scale levels:

- Matching of evidence of 4th scale order 'climato-cyclic' events of global significance that are interpreted from the wide-spread unconformity-bounded genetic sequences.
- Matching of palaeoclimatic evidence preserved in small-scale sequences and soil complexes in order to bridge the gaps between two subsequent global-scale events.

Considerations about this approach have been discussed in *section 2.5.3*.

6.2 Trend-matching of the land-based Middle Pleistocene framework with the marine isotope stratigraphy

6.2.1 Connecting the oceanic record with land-based events

The marine isotope stratigraphy reveals eight major cycles of global glaciation within the Brunhes Chron and two more in the upper part of the preceding Matuyama Chron, reflecting an increase in the intensity of glaciations from about 900 ka. The isotopic cycles of approximately the last 700 ka comprise an average 100 ka period frequency of which the durations range from 88 to 118 ka. Although amplitudes differ, the cycles generally end with a $\delta^{18}O$ maximum followed by a strong decrease to an isotopic minimum (= deglaciation/termination).

Pronounced $\delta^{18}O$ isotopic maxima during the last 700,000 years occurred in the final parts of MIS 2-4, 6, 12 and 16 (Shackleton 1987) suggesting that only during these four cold isotope stages have climatic conditions in Europe been sufficiently severe and sustained to permit the Fennoscandian ice-sheets to expand into the area south of the Baltic (Boulton *et al.* 1997). Moreover, these most intensive $\delta^{18}O$-peaks seem to coincide with the thickest units in the loess-palaeosol record, i.e. the cycles B, C, F and H in the Central European succession (Kukla 1975). On the other hand, there are the weakly expressed $\delta^{18}O$ maxima of MIS 8 and MIS 14 which may indicate periods of less extensive glaciation and loess accumulation. Marine transgressional phases in the North Sea and Baltic Sea margins, immediately following major glaciations, can be fixed to the warm isotope substage peaks succeeding a glacial stage $\delta^{18}O$-maximum[2]. An idealised correlation scheme based on these assumptions then corresponds to *Figure 6.1*.

However, there are ice-sheet developments other than the Fennoscandian/British ones to take into account for the northern hemisphere. Besides minor glaciations that have occurred in Iceland, Greenland and alpine regions such as the Himalayas, the Alps and the Cordillera, the largest part of the total ice volume during the glaciation cycles was the Laurentide ice-sheet on the North American continent. Stratigraphical and chronometric data, mainly K/

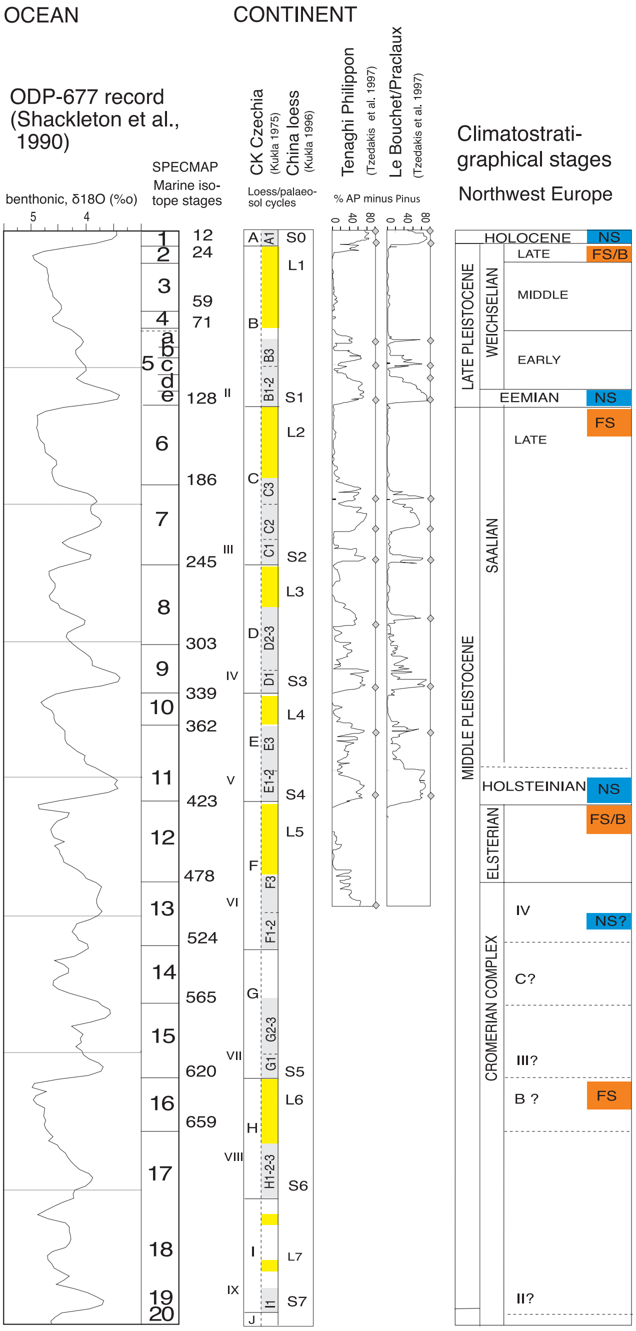


Figure 6.1: Idealised correlation diagram of the Central European terrestrial loess records (Kukla 1975) and Northwest European climatic 'stages' (including the Fennoscandian/British glaciations and North Sea marine transgressions) with the marine isotope record ODP-677 and the MIS. The loess record of China (Kukla 1987) and the local pollen records from Tenaghi Philippon and Lac du Bouchet (taken from Tzedakis *et al.* 1997) are given for comparison.

Ar and Ar/Ar dates from tephras intercalated in glacial sequences in the Cordilleran region, demonstrate that the late Quaternary glaciation events correspond rather well with the marine isotope record. However, this direct correlation should be considered tentatively (Fullerton & Richmond 1986) and is no proof for the expansion of the Laurentide glaciations. Independent radiometrical dates from a calcite vein at Devil's Hole, Arizona (Winograd *et al.* 1992) largely confirm these palaeoclimatic trends, although there are differences in phases and amplitudes compared to the marine isotope stages which have to be explained in more detail.

Marine isotope and regional glaciation maxima may not therefore always be exactly synchronous. Moreover, maximum glaciation limits of the different continental ice-sheets do not necessarily correspond to each other nor do they coincide with the most extreme $\delta^{18}O$ isotope maxima. Such properties may explain the remarkable discrepancies in the number and distribution of glacial sedimentary cycles recorded in the fragmentary Middle Pleistocene regional sequences of mid-latitude Europe. In spite of this indistinct relationship between the amplitudes of the isotope ratios and the regionally different glaciation limits, the trends in the oxygen isotope curves can at least be used as a basis for further confining the independent terrestrial chronostratigraphical evidence from the European non-glacial terrestrial record, such as regionally dated volcanic ash layers, secondary carbonates and biostratigraphical markers.

6.2.2 Connecting the terrestial record with marine isotope events

The correspondence of the terrestrial large-scale events to the marine isotope stratgraphy is closely related to the following questions:

- During which parts of the MIS-intervals were duration and intensity of cooling sufficient to produce ice-sheet expansions into the southern Baltic and further, into the southern North Sea basin and the Russian Plain, and how do these relate to the northern Alpine glaciations?
- To which periods of periglacial loess deposition in Central Europe and Asia do the glacial cycles correspond?
- To what extent does climatic and neotectonic evidence from (unconformities in) the fluvial terrace systems relate to the glacial cycles?

Much of what is known about these points comes from the well-documented chronostratigraphy and climatic history of the Late Pleistocene. It is generally agreed that the Weichselian Fennoscandian, Devensian British and Würmian Alpine cycle B glaciations correspond to MIS 2-4, coinciding with the loess accumulation of cycle B (Kukla 1975) in the Central European extraglacial areas. Maximum glaciation limits were reached during MIS 2, a less extensive ice-sheet advance occurred during MIS 4, but did not spread outside Scandinavia. Radiocarbon dates estimate the age of the Weichselian glaciation maximum just south of the Baltic in MIS 2 at about 20 ka BP[3] (Boulton *et al.* 1985). Modelling suggests that ice-sheet advancing over lowland Northwest Europe during the Weichselian glaciation was restricted to the time period between 25 -18 ka (Van Weert *et al.* 1997). The durations of earlier ice-sheet cover peripheral to the Fennoscandian Shield probably never exceeded 20,000 years. Deposition of loess in periglacial deserts hold a wider time-range. Indicative for the duration in which deposition may take place, although not continuous, may be the period from MIS 4 through MIS 2 comprising some 60 ka. Because of their polygenetic character, fossil soils in first instance give overall time-ranges filling the gaps in between two successive MIS-fixed subaerial units in which they have formed. Since preservation potential is highest for the lowermost B(t)-horizon, representing the first post-sedimentary soil formation processes, these may therefore be equated to the warm marine isotope substage following the loess accumulation.

The Eemian sea-level maximum in the North Sea and the land-based Eemian Stage type forest vegetations broadly correspond to MIS 5 substage e (*cf.* Sánchez-Goñi *et al*. 1999). Stratigraphical relationships and glacio-isostatic interference in the North Sea basin confirms the dating of the transgressive marine sequences succeeding a major glaciation event, a phenomenon which is less clear in the marine terraces along the Channel or the Atlantic coast. Durations of transgressional phases covering the southern North Sea may be in the order of some thousands to 10 ka. Timing of the highest sea-levels however is regionally determined (Mörner 1980, Lambeck 1993).

The correspondence of the Saalian Fennoscandian glacial cycle C to MIS 6 is generally accepted nowadays. MIS 6 also most probably includes the youngest Alpine Rissian (III) glaciation and the Central European loess C accumulation. Some reservations have to be made for Eastern Europe where correlation of glacial sequences appears to be more complicated.

Serious chronostratigraphical problems arise further back in the Middle Pleistocene. This is illustrated in the correlation scheme of *Figure 3.2* compiled by Kukla (1977). In particular the age, or better time-range, of the Fennoscandian Middle Pleistocene glaciation events is not entirely resolved. Although the Elsterian glaciation has produced a distinct glacial sequence, its chronostratigraphical position has remained a matter of debate until recently. Since the first volcanic products of the East Eifel region, K/Ar- and Ar/Ar-dated at about 600 ka, underlie the Elsterian glacial sediments in the southern North Sea basin, this glaciation cannot be as old as MIS 16. Because Mollusca in the subsequent marine Holsteinian North Sea sequence are dated to older than 300-350 ka, i.e. equivalent or older than MIS 9, the Elsterian glaciation must be assigned either to MIS 12 or 10. Correspondence with the latter must be taken into account because of different stratigraphical interpretations and interregional correlations. Both options will be discussed. The Elsterian glaciation is assumed to be time equivalent with the oldest Alpine Rissian (I) glaciation.

Wide-spread glacial sequences predating the Elsterian glaciation are, outside Scandinavia, only found in eastern Europe. The southernmost glaciation limit is found in the Don river basin in the Russian Platform type area. Since its stratigraphical position is below the *Mimomys/Arvicola* boundary, which is contemporary in the Middle Rhine region with the first East Eifel volcanic activity at about 600 ka, and its deposits are normally magnetised, the Donian glaciation most likely corresponds to MIS 16. On other grounds, this may also be true for the northern Alpine Mindelian glaciation.

The lower boundary stratotype of the Middle Pleistocene at the Brunhes/Matuyama geomagnetic reversal approximates to the MIS 20/19 transition at termination IX. Since there are no clear 4th-order climatic signals prior to the Donian glaciation, no related event-stratigraphical boundary levels can be set for this period.

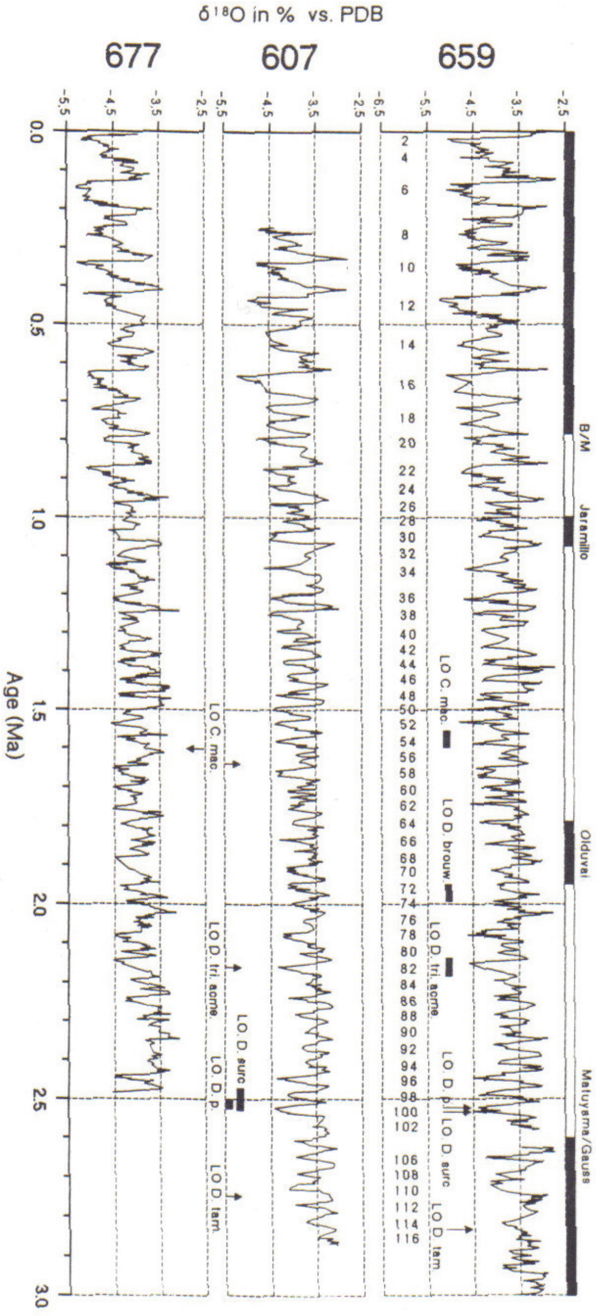


Figure 6.2: Correlated (benthic) δ^{18}O core records from ocean sites ODP 607, ODP 677 and ODP 659 (taken from Tiedemann *et al.* 1994). Records are plotted using the site 677 timescale. Isotope stages are labelled. Age ranges for palaeomagnetical and biostratigraphical boundaries are plotted for comparison.

6.3 Global time-stratigraphical settings for the terrestrial Middle Pleistocene subseries

6.3.1 Marine isotope stage boundaries: scale and resolution

The ratio of the ^{18}O/^{16}O-isotopes as preserved in the rests of fossil foraminifera in the deep-ocean sediments is dated by ^{14}C, U/Th and palaeomagnetic reversals, mostly by extrapolation. Since the mid-1970s its record has recurrently been calibrated with new palaeomagnetic data and has been statistically tuned with the astronomical time scale of the Earth's orbit (Hays *et al.* 1976, Johnson 1982; Imbrie *et al.* 1984; Martinson *et al.* 1987, Shackleton *et al.* 1990, Lourens *et al.* 1996). This has provided a relatively high resolution time scale. Imbrie *et al.* (SPECMAP group 1984) have generated a synthetic signal of global ice-sheet fluctuation for the last 0.75 Ma. Their isotope curve was constructed from many core sequences from the northern hemisphere and therefore is an average signal. Timing of the marine isotope stages, however, differs slightly between the different cores. Notwithstanding, the trends are confirmed from several single deep-sea core records by Martinson *et al.* (1987), and later Shackleton *et al.* (1990: using the Pacific ODP-677 lag) and Bassinot *et al.* (1994; using the Atlantic ODP-607 record off Morocco) among others. Since the SPECMAP record was calibrated to about 700 ka, the latter two cores (*Fig. 6.2*), extending through the whole Quaternary Period, are used here as reference profiles for the early Middle Pleistocene.

The stage boundaries, as defined by the SPECMAP group, are rather arbitrarily placed at the midpoints of the steep (δ^{18}O increases, i.e. at the terminations of the glacial-interglacial transitions (*cf.* Broecker and Van Donk 1970). Terminations are compromise dates which serve as worldwide averages for the age of the *deglaciations*. Deglaciations comprise relatively short intervals of exceptionally rapid δ^{18}O-increases in the ocean waters, as a result of rapid melting of ice-sheets, starting from a 'full glacial' maximum into an 'interglacial' optimum (*cf.* Kukla and Cilek 1996). These rapid climate changes represent the least *time-transgressive units* in the marine isotope stratigraphy, although their time intervals range from 10 to 20 ka. Nevertheless, the fact that several time-transgressive boundaries of the relatively-dated mid-latitude terrestrial sequences lie within these deglaciation intervals can serve as a basis for extrapolation and correlation of interpreted events and isotope stages at a glacial-interglacial scale.

Because of their wide time-range, the MIS transitions only provide a rough indication of the timing of the terrestrial boundary levels. How accurate are the stage boundaries of the oceanic isotope record for use as arbitrary 'remote' boundary levels in the lack of terrestrial alternatives? The problem of using boundaries in the ocean-core isotope profiles is one of scale. It is very difficult to identify where boundaries should go when the scale of the isotope plots is so small. The detail is not always visible and time lags of up to thousand years must be considered because of bioturbation (Shackleton 1977). Moreover, the boundaries between the isotope stages are not drawn at fixed points in the marine sequences. They are graphic artefacts and do not represent real natural events. The variability of the timing of the isotope stages in different cores is the result of a combination of the graphic interpolation of the terminations and the impact of bioturbation. They together limit the chronostratigraphical resolution of ocean-bottom sediment. Therefore it is not possible to use the isotope sequences for 'golden-spike' boundary definition. Dates for the boundaries between the MIS transitions are thus in reality rather difficult to determine, extrapolation being the only reliable way of achieving a relatively reliable number.

6.3.2 Marine isotope stage boundaries and their terrestrial equivalents

Boundary stratotypes in the Middle Pleistocene terrestrial sequences are relative and lack adequate chronostratigraphical definitions (*chapter 2*). Chronological control to define (sub)stages is largely missing. The recommendation in the last edition of the ISG (Salvador *et al.* 1994), to fix corresponding physical marker units as intervals between designated boundary stratotypes, only applies to the Brunhes/Matuyama geomagnetic reversal as the lower boundary of the Middle Pleistocene. There are, however, no such other boundaries at or close to critical positions within the Middle Pleistocene sequences and palaeoclimatic events. The boundary levels in the marine isotope stratigraphy are a reasonable alternative, although they cannot form the basis for a classification or chronology of the land-based sequence. They are used as event-stratigraphical reference boundaries for comparing the spatial and temporal variability of their terrestrial equivalents. Kukla's 'marklines'[4] in the stacked loess sequences of Central Europe, the lower bounding unconformities of coastal marine sequences in the North Sea margins and the increasing tree pollen contents in pollen records from lake sequences, are, notwithstanding their diachronism, boundary levels of climate-driven events corresponding to different starting points within the global-scale deglaciation intervals.

Available local records and dates may provide a more precise age and may gain higher resolutions within the deglaciation intervals. The deglaciation phase of MIS 6, which began roughly from about 150 ka, to the warm climatic event of MIS 5 substage e is well documented and known in more detail from other types of records: a) δ^{18}O-records from ice cores (GRIP-members 1993) and several oceanic cores, b) ice-rafted detritus accumulation rates from marine records in the Norwegian Sea (Baumann *et al.* 1995, Mangerud *et al.* 1996, and compared with glacier fluctuations in Western Scandinavia), c) foraminiferal analysis of shelf records from Denmark (Seidenkrantz 1993), d) pedostratigraphical records from France (Van Vliet-Lanoë 1995, Antoine 1997), pollen assemblages from marine cores off-Portugal (Sánchez-Goñi *et al.* 1999) and f) speleothems from Norway (Lauritzen 1991, 1995). This evidence reveals high order climatic fluctuations, of the Younger Dryas type, among which a short-termed climatic oscillation at about 130-135 ka just prior to the MIS 6-5e boundary level at 128 ka: the Zeifen-Kattegat oscillation (Seidenkrantz *et al.*1996). Whether this deglacial climatic fluctuation represents the Warthe re-advance phase is not clear as yet. Evidence for an independent Warthe glacial cycle is weak, however, since most evidence from non-glacial intermediate sequences has not revealed a marine transgressional maximum in the North Sea basin nor a full forest vegetation climax in lacustrine sequences overlying the regional Drenthe/Odra/Dniepr synthems (*section 4.3.1*).

Direct correlation of pollen evidence in deep sea-cores off the Iberian peninsula confirms an event-stratigraphical relationship with the δ^{18}O-minima peak for MIS 11, the Holsteinian (Desprat *et al.* 2005), corresponding with a 32,000 year forest vegetation record. The time-range of forested periods is variable and geographically determined. Vegetation cycles, such as those in the lake sequences from Tenaghi Philippon and Lac du Bouchet, also reveal shorter climatic oscillations which may match marine isotope substages. They need, however, a MIS-fixed base for matching. In some cases time lags may be very short as is shown by varve counting in lacustrine records from Marks Tey (Turner 1970) and Bilshausen (Müller 1974).

6.3.3 Tentative substage boundary levels for the Middle Pleistocene in Northwest and Central Europe

The relatively well-dated last deglaciation phase (MIS 2/1) took place between about 18 and 6 ka BP. The age of termination I is dated at about 12.5 ka (Bard *et al.* 1992), but is time-transgressive between about 9 and 13 ka from different deep-sea cores. This date could logically be taken as the global Pleistocene-Holocene boundary level. Based on land evidence, the formal lower boundary of the Holocene for practical reasons is placed at 10 ^{14}C ka BP by the INQUA-Commission on Stratigraphy (Hageman 1969) in the absence of an internationally defined stratotype or GSSP. A boundary stratotype is now being defined in the NGRIP ice-core on Greenland (Walker *et al.* in press).

Just as the lower boundaries for the Holocene Series and for the Late Pleistocene Subseries, arbitrarily defined at 128 ka (termination II) within the deglaciation phase of MIS 6 to 5e between 135 and 122 ka (Gibbard 2003), at least two provisional Middle Pleistocene lower Subseries boundary levels valid for both the glaciated and non-glaciated areas in Northwest and Central Europe are placed here at relevant deglaciations further back in the marine isotope record:

- The lower boundary level of the late *Middle Pleistocene* corresponding to the deglaciation of MIS 12/11 substage c for which an average date of 423 ka (termination V) is interpolated (*section 6.3.3*),
- A lower boundary level within the *early Middle Pleistocene* corresponding to the deglaciation of MIS16/15 at about 620 ka (termination VII), subdividing this period into an part A followed by a part B that begins at the 620 ka point (*section 6.3.4*). The base of the early Middle Pleistocene coincides with that of the Middle Pleistocene, i.e. the B/M boundary, as is proposed by Richmond (1996).

Fixing the terrestrial boundary levels to these MIS transitions is of importance because they confine the timing of the most extensive Middle Pleistocene glaciations and of the loess/palaeosol cycles in Northwest and Central Europe, which represent the main building blocks of the regional stratigraphies within the continent-wide framework. The correlation scheme in *Figure 6.3* is based on these links between the oceanic and the terrestrial mid-latitude European Middle Pleistocene sequences and will be a guide in the next sections in discussing facts and arguments on the chronostratigraphical positions of the latter.

6.3.4 Evidence for the early / late Middle Pleistocene boundary level at the MIS 12/11 transition

In Northwest Europe this boundary level represents the chronostratigraphical boundary between the Elsterian Stage and the Holsteinian temperate Stage. Of crucial importance for their correspondence to the marine isotope stratigraphy is the timing of the coeval Fennoscandian and British cycle F glaciations and the subsequent Holsteinian marine sea-level maximum in the North Sea type region. Interregional correlation of these large-scale events with other regional stratigraphies, such as with the upstream Lower and Middle Rhine stratigraphy, the Central European terrace and loess stratigraphy, and with the reference pollen record of Lac du Bouchet in the Massif Central, relies on:

- The tephrochronology in the East Eifel region,
- The stratigraphical position of the tephras interbedded in the Middle Rhine subaerial and fluvial sequences,
- The heavy mineral composition of the subaerial and fluvial sequences in this area and downstream of the river Rhine,
- Various biostratigraphical markers in fluvial and lacustrine sequences and
- The relative time correspondence of the remarkable erosional breaks in several early Middle Pleistocene river terrace systems.

The best dates to estimate the lower boundary level for this division with are between 370-450 ka, coming from K/Ar- and Ar/Ar-dates of pyroxene-rich tephras attributed to the Rieden phase of volcanic activity in the East Eifel region. These markers are represented in the Middle Rhine Kärlich H sequence, at Miesenheim I and in and above the Middle Rhine mMT gravel terrace sequence at Ariendorf. Their intercalated tephra beds have been dated at around 450 ka and are associated with cold-climate conditions equated to MIS 12. The palaeosol complexes on top of these cold period units are overlain by tephras dated to between 370 ka (Kärlich *Brockentuff*) and 420 ka (Ariendorf *Selbergit tuff*), which can therefore be attributed to MIS 11. The predominance of pyroxenes in the heavy-mineral assemblages in the upper part of Middle Rhine Kärlich G sequence and in the mMT terrace gravels indicate that the pyroclastic deposition was already taking place during MIS 13 and continued into MIS 12 and MIS 11.

The dates for the East Eifel Rieden eruption phases in the Middle Rhine fluvial and subaerial sequences, together with the MIS trend matching, are used to determine the timing of the subsequent erosion, northward fluvial transport and incorporation of the derived volcanic minerals in the alluvial sediments of the Anglo-Dutch/North Sea sub-basin. Since high augite contents first occur in the heavy-mineral spectra of the North Sea Noordbergum marine intercalation (= Cromerian IV Substage *cf.* Zagwijn) this early Middle Pleistocene sea-level highstand can be assigned at the earliest to MIS 13. Based on the stratigraphical position of the Elsterian glaciation in this type region, intermediate of augite-rich fluvial synthems of the Anglo-Dutch North Sea Urk sequence group, it can be concluded that MIS 12 is the best option for its correspondence to the oceanic isotope record. The maximum extent of the Elsterian glacial advance then took place prior to the release of the augite-containing *Selbergit tuff* in the East Eifel region and subsequent fluvial transport by the river Rhine to the north.

Based on similar interregional correlations with the Dutch stratigraphy, but using early radiometric dates on the release of the augite-bearing *Selbergit tuff* at around 400 ka, Zagwijn (1986, 1992) attributed the marine North Sea Noordbergum intercalation to MIS 11 and the subsequent glacial advances of the Elsterian glaciation to MIS 10. In this option the early/late Middle Pleistocene boundary level would be assigned to the deglaciation of MIS 10/9 (termination IV at 339 ka). This differs from by about 100,000 years with the present proposal[5], assuming that deposition of augite-rich alluvial sediments in the Anglo-Dutch North Sea subbasin may already have taken place during a 100 ka cycle earlier, that is from MIS 13.

Additional evidence for equating the lower late Middle Pleistocene boundary level with MIS12/11 comes from biostratigraphical evidence of marine and lacustrine deposits assigned to the Holsteinian Stage s.s. and their supposed correlation with the Praclaux forest vegetation optimum in the Massif Central Lac du Bouchet maar lake record. The late-temperate phase of many 'Holsteinian' pollen spectra contain the last appearance datum (LAD) of *Pterocarya* pollen which is tentatively used as a biostratigraphical marker in the reference pollen record of the Lac du Bouchet that coincides with MIS 11 (De Beaulieu and Reille 1995). Since these pollen records represent the first forest climax of interglacial type following the Elsterian/Anglian glaciation maximum and accompanied by high sea-level stands in the North Sea area, they most likely correspond to substage c of MIS 11. Furthermore, lower and middle section fine-grained fluvial channel deposits of several European rivers contain *Pterocarya* pollen and the characteristically Holsteinian mollusc *Viviparus diluvianus*. Among others, the so-called '*Krefeld clay beds*' in the Lower Rhine Embayment type region which lie conformably on top of the MTIIIa- or '*Rinnenschotter*' cold period aggradation, equivalent to the Middle Rhine mMT sequence and attributed to MIS 12.

The absence of *Pterocarya* in the forest pollen assemblage of the Middle Rhine Kärlich Seeufer lake sequence, dated to the first warm climate event following the deposition of the *Brockentuff* at 396 ± 20 ka, points to correspondence with MIS 9 and confirms the timing of the Elsterian-Holsteinian boundary level at the MIS 12/11 transition. This conclusion is supported by most dates on carbonates and fossils from Holsteinian Stage deposits (*section*

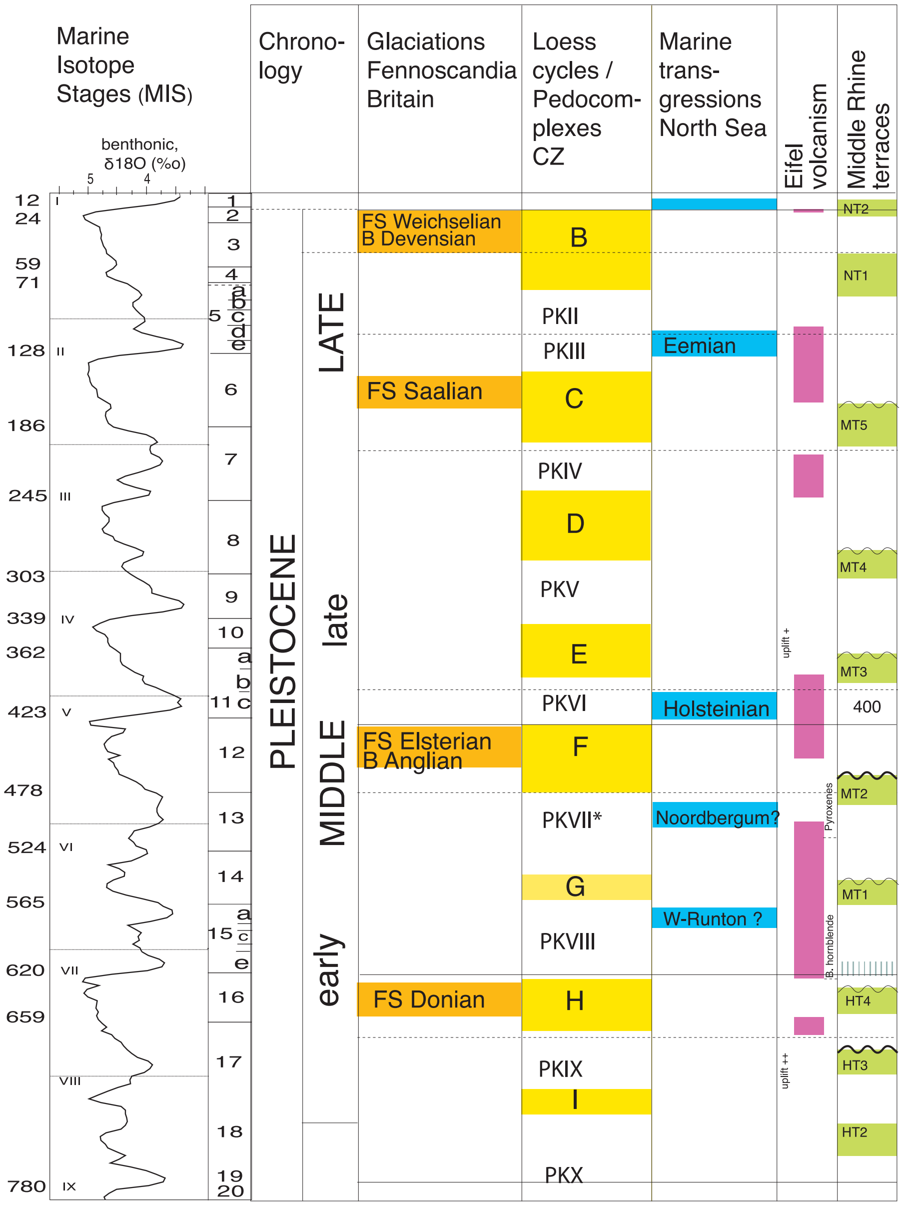
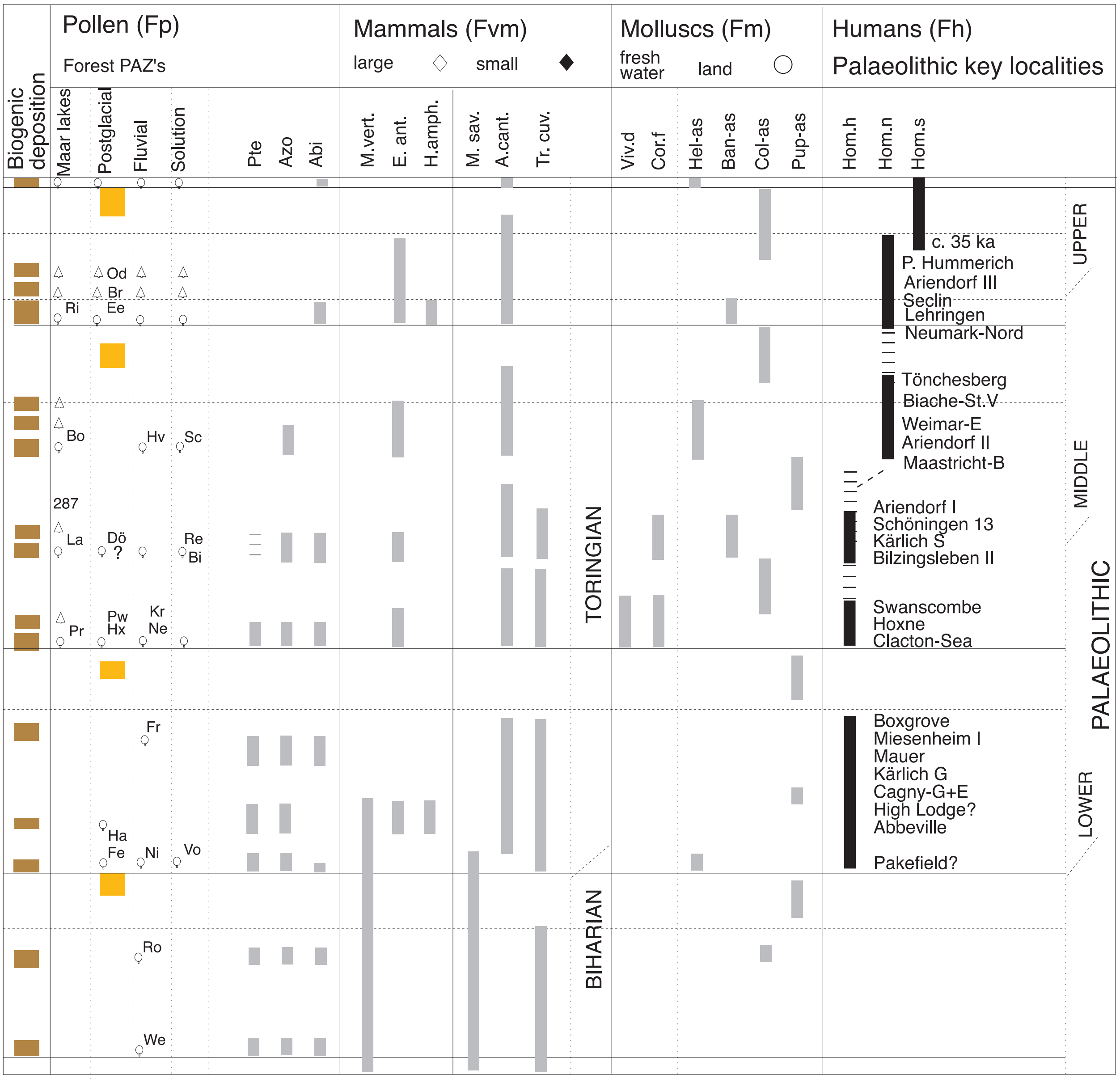


Figure 6.3 Correlation of the terrestrial event-stratigraphical subdivision of the Middle (and Late) Pleistocene for Northwest and Central Europe with the marine isotope stratigraphy, on a linear time scale.

3.4.3). Similarly, Ehlers, Gibbard & Rose (1991) for Europe attributed MIS 11 as the most probable correlative of the Holsteinian Stage, as most workers from Britain and the European continent do today.

Indirect correlation of the strong basal unconformities of the pyroxene-dominated mMT- and '*Rinnenschotter*' synthems in the Middle Rhine and Lower Rhine Embayment type regions and of the subaerial Kärlich H I synthem, dated between 450 and 500 ka, with similar erosional phenomena documented in other Central European terrace (and loess) sequences, may provide a link between the chronostratigraphical position of the Elsterian glaciation and fluvial response to tectonic movements in the extraglacial stratigraphies (*section 4.4.3*). The exceptionally deep incision phase in the Rhineland type regions is also found in, and may be correlative with, a) the middle sections of the Elbe drainage basin, where the so-called '*Frühelsterterrasse*' (EET) sequence is immediately overlain by the Elsterian glacial sequence, and b) the terrace stratigraphy of parts of the Danube drainage basin. The latter concern the erosional breaks separating the northern Alpine Foreland alluvial Younger *Deckenschotter* supersynthem from the *Hochterrassen* supersynthem and the eastern Alpine Foreland Červený Kopec 3 fluvial terrace sequence from the CK2 terrace sequence. The initial age of these dissimilar downcutting and aggradation phases is intermediate between the Central European pedocomplex PKVII and the thick Central European loess unit F which are correlated to MIS 13 and MIS 12, respectively. Since



the erosional breaks are provisionally linked with fluvial response to (glacio-)isotatic rearrangements by Kukla and Çilek (1996), they may support their conclusion that the extensive Elsterian/Anglian/Alpine oldest Rissian (I) glaciations were responsible for these fluvial anomalies in the extraglacial areas and for the extreme changes in erosion base levels in the North Sea basin. Subsequent infilling of the incised valleys and the subglacial channel system, e.g. the Peelo Formation in the Netherlands, probably took place during the ice-sheet maximum close to the end of MIS 12.

To conclude: the assignment of the early/late Middle Pleistocene boundary level at the MIS 12/11 transition in the marine isotope stratigraphy (*Fig. 6.3*) would solve the chronostratigraphical problems concerning the north European glacial models in the correlation scheme (*Fig. 3.2*) and establish a link between the glacial and extraglacial terrace and loess stratigraphies. This lower boundary would then represent:

- The transition of the glacial deposits and unconformities associated with the Fennoscandian, British and Alpine glacial cycle F (Elsterian, Sanian 2, Okian, Anglian and the oldest Rissian) to the Holsteinian (Hoxnian, Mazovian and Likhvinian) non-glacial sequences of marine, lacustrine and fluvial origin in the glaciated type areas, including the transition to forest vegetation in these,
- The transition of the subaerial synthems equivalent to the Central European loess cycle F to the formation of soil complexes correlative with PKVI,
- The transition to the (coeval) fluvial sequences following the erosional unconformity of Central European cycle F in the terrace systems of the extraglacial type areas.

6.3.5 Evidence for the MIS 16/15 boundary level within the early Middle Pleistocene

Terrestrial evidence for an event-stratigraphical boundary level within the lower Middle Pleistocene succession coinciding with the MIS 16/15 transition (midpoint at 620 ka: termination VII) is only well-documented in eastern Europe. There the boundary level represents:

- The transition of the glacial sequences correlative to the Fennoscandian cycle H (Donian, Sanian I, Narevian, Servackian) glaciation event to the Russian Plain Muchkap and Polish Plain Ferdynandov non-glacial sequences of lacustrine and fluvial origin,
- The transition of the Russian Plain Borisoglebsk loess cycle to the formation of soil complexes correlative with the Russian Plain Vorona soil complex.

The latter transition is contemporary with that of the Central European loess cycle H to the soil complexes PKVIII and PKVII in Central Europe. PKVII contains rubified Bt-horizons (‘*Braunlehm*’) of forest soils among others, which are associated with intense warm and humid climate conditions probably during MIS 13. They are also found in several other type regions, among which the northern Alpine Foreland (‘*Riesenboden*’). Here the Alpine Mindelian glaciation predates these pronounced soils of Bt-type and therefore most probably can be equated with the Donian glaciation.

Distinguishing criteria of the subsequent Russian Plain Muchkap/Polish Plain Ferdynandov lake sequences concern:

- The presence of the *Mimomys-Arvicola* boundary,
- A characteristic bi-optimal warm stage type floral succession.

Although evidence of wide-spread cold climate events prior to the Elsterian glaciation is scanty in Northwest and Central Europe (*section 4.3.1*), extrapolation of this biostratigraphical evidence and interpreted palaeoclimatic and -environmental features also seem to justify a subdivision of the early Middle Pleistocene in these type areas. Their correlation with regional event-stratigraphical markers and independent dates show that:

- The *Mimomys-Arvicola* boundary in the Kärlich section occurs between the deposition of loess synthem F and the first depositional cycle of Kärlich subaerial sequence G. It, however, post-dates the Bt-type soil complex developed in loess unit F which is equivalent to MIS 15 (substage e),
- The West Runton marine synthem in East Anglia indicates a transgression in the North Sea basin which may correspond to MIS 13 or MIS 15 (substage a) and post-dating the Donian glaciation. Unfortunately, stratigraphical control is lacking and there is no equivalent in the North Sea basin. The estuarine deposits are overlying the warm-stage sequence of the West Runton Freshwater Bed (West 1996), containing *Mimomys savini*, and comparing well with the pre-Elsterian Voigtstedt warm-stage fluvial lake sequence in Germany based on mammal fauna,
- The *Mimomys-Arvicola* boundary roughly coincides with the first subaerial and fluvial synthems in the Rhineland that are characterised by the dominance of derived volcanic minerals, in particular brown hornblende, associated with the increase of East Eifel volcanic activity starting from about 570 ka and hence post-dating MIS 16/15 boundary level,
- This increase in volcanic activity follows the tectonic-induced transition of the Middle Rhine and Lower Rhine Embayment Upper Terrace (HT) sequence group to the Middle Terrace (MT) sequence group in these type areas. It also corresponds to the northward shift of the Lower Rhine course geographically separating the Lower Rhine Sterksel and Urk alluvial sequence group. The MIS 16/15 boundary level probably lies within the hiatus between their aggradation phases,
- The pronounced warm-climate soil complexes in the Lower Rhine Embayment HT3 and HT4 terrace sequences (‘*Ville*’) is equivalent to the pedocomplexes PKVIII and PKVII in Central Europe and probably correspond to the period MIS 15 to 13,
- The lake sequences of Harreskov and Ølgod (Andersen 1965) in Denmark rest on glacial sediments and their forest vegetation climaxes are very similar to that of the lowermost in the Polish Plain Ferdynandovian glacial lake sequence.

This evidence on the timing of the early Middle Pleistocene event markers and their correspondence with the MIS suggests that the transition of MIS16/15 is, at least for eastern Europe, a relevant boundary level for subdividing the period into a part A and a part B (*Fig. 6.3*). A complicating factor forms the *Mimomys-Arvicola* boundary which is post-dating the first Bt-soil horizons developed on the Central European loess units of cycle H and in the Middle Rhine Kärlich loess sequence F and therefore cannot be attributed to the first substage (e) of MIS 15. In addition, the position of the MIS 16/15 boundary level within the ‘Cromerian Complex’ Stage remains unclear. This will be discussed further in *section 6.4.2*.

6.4 Middle Pleistocene local-scale event correlations and integration of Palaeolithic sites

With the wide-spread evidence of the large-scale events representing the Middle Pleistocene loess depositional cycles in Eurasia and Central Europe, the glacial depositional cycles in northern Europe and the marine transgressional cycles in the North Sea basin, arranged within the MIS-fixed time frame (*Fig. 6.3*), a suitable chronology on the basis of event-stratigraphical criteria and indirect correlation for both the loess stratigraphy and the classical European glacial models has been established. This also corresponds to the megacycle principle of Kukla and Çilek (1996) based on the loess depositional cycles in China and Eurasia, although the lower boundaries of the units are set at the base of the Central European loess units: megacycle (MC) 1 starts with loess unit C, MC2 with loess unit F and MC3 with loess unit H. The loess units are equivalent to the Fennoscandian glacial sequences C (Saalian), F (Elsterian) and H (Donian), respectively.

The global correlations prove that a substantial part of the time represented in the Middle Pleistocene terrestrial records is locked in unconformities and intermediate sequences which are predominantly locally controlled and preserved. The correlation scheme in *Figure 6.3* will be used as a guide for summarising the development and stratigraphical positions of the local-scale Northwest and Central European events. The interpretation and correlation of these events have given much debate among researchers (*chapter 2*). Although their palaeoclimatic information, such as vegetational forest climaxes of warm-stage character in lakes and mires, modes of river deposition and soil complexes, also involve higher order (short-term) cyclicities/oscillations and local neo-tectonic effects, they nevertheless should correspond to the global-scale MIS-fixed framework. The nearest reference vegetational proxy records are those of Lac du Bouchet (Southeast France) and Tenaghi Philippon (Greece) which are also shown in *Figure 6.3* for comparison. Latitudinal and altitudinal differences in vegetational and soil development should be taken into account. Correlations of local evidence should be achieved by following the post-depositional succession from a large-scale MIS-fixed basal, unconformity-bounded, unit or a dated level upwards. The largest hiatuses are expected after levelling of glacial relief and below the next global-scale unconformity since erosional processes of their related events have generally removed the upper parts of the preceding post-depositional succession.

Within the scope of this research project, referred to in the preface, some conclusions on the stratigraphical position of Palaeolithic sites in Northwest and Central Europe within the MIS-fixed time frame are also integrated in *Figure 6.3* and discussed below.

6.4.1 Stratigraphical position of Late Middle Pleistocene local events (MIS 11-6: 423-128 ka)

The late Middle Pleistocene 'superstage'[6] spans about 300 ka and is correlative to MIS 11-6 between the boundary levels of MIS 12/11 (termination V at 423 ka) and MIS 6/5 (termination II at 128 ka). Its sequences are based by the Elsterian Fennoscandian glacial sequence F in northern Europe and CE loess sequence F, and equivalents, in the non-glaciated areas.

The best reference for warm palaeoclimatic events in Europe is the Lac du Bouchet pollen record, which shows seven forest vegetation climaxes during this time interval. The last occurrence of *Pterocarya* pollen in the forest assemblage zone of the Praclaux event (MIS 11) is a significant biostratigraphical marker for correlation. MIS 11 represents a period of marine transgression in the North Sea basin, small-scale fluvial deposition (with characteristic temperate freshwater molluscs), soil formation and local lake sedimentation showing a single climatic optimum in their pollen content and containing *Pterocarya* in a late-temperate phase. These sequences form the lower boundary of the late Middle Pleistocene in the glaciated type regions.

Firm evidence for large-scale (4th order) climatic events intermediate between the Holsteinian North Sea sea-level maximum and Saalian glaciation is largely missing in the European lowland areas because, next to the poor accessibility, extensive glaciation limits are not recorded. The cold MIS 10 and MIS 8 apparently constitute ice-free periods in the Northwest European lowlands. In Poland, on the other hand, evidence is found for ice-sheet expansions beyond the Fennoscandian Shield during the cold MIS 10, the Liwiec glaciation (Lindner 1988), separated by warm intervals. Unfortunately, the intercalated organic sediments here are not superimposed, which hampers correlation (Krzyszkowski 1991). In the western part of northern Alpine Foreland the Rissian II or '*Doppelwall Riss*' glaciation has been assigned to MIS 10 (Ellwanger *et al.* 1995).

Glacioeustatic sea-level maxima in the North Sea did not reach the present coast-line. There are, however, indications of high sea-level stands on the Atlantic coast and in the Channel area. Oceanic climate influence was very limited during MIS 7, because of the absence of *Abies* from the, few available, pollen spectra. Nevertheless, Meijer and Cleveringa (2003) on the basis of AAR data from molluscs report a marine transgression in the Netherlands during a warm event, introduced as Oostermeer, dated within MIS 7.

Most lake basins became silted up after MIS 11. At least the first part of one warm-climatic episode following the Holsteinian Stage is recorded in the North Sea basin margins at Wacken and Pritzwalk. These Wacken and Dömnitz warm events may be assigned to MIS 9(c). Further biostratigraphical evidence is predominantly preserved in upland small-scale basins related to local salt-tectonic features, denudation and volcanics, all of which show slightly non-standard pollen spectra, and in travertine springs, e.g. Bilzingsleben. The lake sequence of Bilshausen in the Thuringian Basin spans the entire MIS 9 (*section 5.2.3*). The age of the Middle Rhine Kärlich Seeufer (landslide) lake sequence can be dated in a warm event younger than 370 ka, implying that its vegetation optimum also corresponds to MIS 9. The lake and mire sequences of the Schöningen section (*section 5.4*) reveals at least two warm-climate type forest climaxes separated by major unconformities: the Reinsdorf warm climate event and the Schöningen warm climate event which can be attributed to MIS 9 and MIS 7, respectively. The stratigraphical positions of other local pollen evidence, e.g. Hoogeveen, Zbojno, is too uncertain to reach a firm conclusion regarding their ages, although their forest climaxes may point to correlation with MIS 9. Zagwijn (1990) tentatively considered the Hoogeveen temperate interval to belong to MIS 7. This period is also correlated with fine-grained fluvial deposits of the river Meuse at Maastricht/Belvédère in the Netherlands, that contain Palaeolithic artefacts, and is TL-dated to about 250 ka (Huxtable 1992). This age determination is in accordance with U/Th dates of 177-234 ka from the Schöningen peat deposits (Heijnis 1994).

Several late Middle Pleistocene archeological sites span the period MIS 11 to 6. On typological grounds, as well as on dated geological evidence, at least two phases of occupation can be distinguished during this period between the Elsterian and the Saalian glacial maxima (*Fig. 6.3*):

- One group dates from MIS 11 to 9. There is evidence for occupation during the late-temperate phases of two climatic optima. The first optimum coincides with the Holsteinian North Sea marine transgression and biogenic lake deposits that can be tentatively correlated to MIS 11c, globally dated around 420-400 ka BP. It should be noted that only British examples are known: Hoxne and Clacton-on-Sea. Archaeological findings from more eastward German sites, at Kärlich-Seeufer, Schöningen 13 (=Reinsdorf) and Bilzingsleben II, date from a later climatic optimum, which is probably MIS 9 (substage c: *c*. 330 ka BP). These late Middle Pleistocene Palaeolithic sites are the oldest known on the Central European continent.
- The second group of late Middle Pleistocene Palaeolithic sites can beyond doubt be attributed to MIS 7 and early 6, between 250-160 ka BP. They are preserved in travertine, fluvial terrace sediments and buried soils, formed under alternatively warm-temperate and boreal climate conditions.

6.4.2 Stratigraphical position of early Middle Pleistocene local events (B/M boundary - MIS 12: 780-423 ka)

The early Middle Pleistocene traditionally comprises the sequences that can be palaeomagnetically dated from the base of the Brunhes Chron to and including those deposited during the Elsterian glaciation and its most likely extraglacial equivalent, the Central European loess cycle F. The 'superstage' may regionally be further subdivided into a part A and a part B depending on local and regional stratigraphical evidence.

Part B is correlative to the period MIS 15-12. Its base is formed by the glacial sequences of Donian age in eastern Europe and CE loess unit H and equivalents in the non-glaciated areas. This period is striking by the absence of large-scale cold events prior to the Elsterian glaciation in both the glaciated and extraglacial areas. Central European loess cycle G, as well as Chinese loess records, indicate only minor cold in MIS 14, which is confirmed in the Kärlich G subearial sequence in the Middle Rhine type area. Instead, many local sequences are preserved that reflect several warm climatic events that can be attributed to MIS 15 and MIS 13.

During this period the first evidence of hominid occupation in mid-latitude Europe is also found. This corroborates the conclusion of Roebroeks and Van Kolfschoten (1995) that all sound evidence of early human occupation is found in local sedimentary sequences that post-date the Brunhes/Matuyama palaeomagnetic reversal at about 780 ka (MIS 19). Early Middle Pleistocene sites pre-dating the glacial sequences of the Elsterian/Anglian glaciations probable do not exceed MIS 15 in age (*Fig. 6.3*, *Epilogue*). Their communities, associated with bifacial industries, constitute the oldest occupation group which is geographically located in Atlantic western Europe, along the coasts of the Channel, e.g. at Boxgrove, and in the valleys of some large river systems (Somme, Rhine) draining chalk areas.

Part A is correlative to the period corresponding to MIS 19-16. The Brunhes/Matuyama geomagnetic reversal in various local sequences is a clear chronostratigraphical boundary. However, large-scale palaeoenvironmental or palaeoclimatic signals of the 4th order are missing from this time interval. There is also poor bio- and chronostratigraphical control in the non-glacial sequences. Evidence for this period is related to the last event-stratigraphical boundaries in the Early Pleistocene which can probably be set at a glacial maximum that corresponds to MIS 22 (900 ka) and a neo-tectonic cycle boundary of increased uplift rates that began at about 1.2 Ma. Fluvial terrace complexes corresponding to these intervals (MIS 22-16) include the Middle Rhine - and Lower Rhine Embayment Upper Terrace (HT) sequence groups and the northern Alpine Foreland Younger *Deckenschotter* (*section 4.3.3*). The latter contains fluvioglacial deposits dating from the Alpine Haslach glaciation, probably of MIS 22 age, as well as from the subsequent Mindelian (MIS 16) glaciation.

The stratigraphical position of the Northwest European Cromerian events ('Cromerian Complex' Stage) within the MIS-fixed framework remains unclear. The reason for this is that the Cromerian subdivision is mainly based on the fragmentary occurrence of local warm-climate event signals within the Lower Rhine fluvial environments. The Cromerian substages I (Waardenburg[7]), II (Westerhoven) and III (Rosmalen) lack stratigraphical control and are not related to large-scale continental events that can be matched with the marine isotope stratigraphy. Moreover, warmest Cromerian substage localities, reviewed in Turner (1996), are not completely preserved. This makes them difficult to correlate. As is obvious from other environments in the European type regions, as well as from the marine isotope stratigraphy, there are hiatuses in the Cromerian succession particularly between the warm substages III and IV (Zagwijn 1996). The Cromerian IV (Noordbergum) sediments, comprising marine reworked fluvial deposits, are found above the 'augite datum' in the Rhine deposits, the latter related to Eifel volcanism. These marine sediments, as well as those from Ostend (England), contain the earliest remains of the water vole *Arvicola terrestris cantiana* which makes an MIS 13 age very likely. High sea-level stands during MIS 13 may have occurred in connection with the warm climate conditions indicated by the extremely leached forest-soil complexes found at several Central European localities. The high-sea-level stands interpreted from the warm-stage sequence at West Runton, i.e. above the West Runton Freshwater Bed containing *Mimomys savini* (West 1996), may also coincide to MIS 13 or even indicate a potentially earlier marine transgression in the North Sea. This may well have occurred during MIS 15 (substage a), although there is no direct evidence in the area of a preceding Fennoscandian glaciation. The Cromerian III warm interval is difficult to correlate with other evidence that can be equated to MIS 15. Since its stratigraphical position is associated with the Lower Rhine Embayment *Hauptterrassen* sequence group, pre-dating the MIS 16/15 boundary level, this warm interval, as well as the Cromerian II interval, seem to have occurred during the period between MIS 19 and 16.

6.5 Conclusions and outlook

The proposed use of genetic sequence and event stratigraphical procedures, supplementary to the traditional climatostratigraphy, brings about a better understanding of the stratigraphy of the terrestrial Middle Pleistocene sequences. Regional schemes have been proposed herein for the Northwest and Central European type areas. These schemes have been developed by integration of the multidisciplinary stratigraphical evidence into local and regional scale units recognised and defined on the basis of bounding unconformities and depositional environment. This informal subdivision of genetic sequence units provides tools for interregional correlation of the wide-spread glacial and periglacial subaerial sequences. With the help of a set of interregionally significant 'bio'- and 'chrono'-markers from the often localised intermediate units, a preliminary chronostratigraphical framework has been compiled. Subsequent interpretation of different type events, with reference to spatial and temporal scale as a basis for correlation, brings about a better understanding of the climatic and environmental history of the Middle Pleistocene. Relating the event-stratigraphical framework for Northwest and Central Europe with the marine isotope stratigraphy offers possibilities for refining the relative chronology. At least for the late Middle Pleistocene, the terrestrial equivalents of the 4th order glacial-interglacial depositional cycles can be equated fairly accurately to the MIS. With regard to the chronostratigraphical positions of the classical Northwest European palaeoclimatic stages of the Middle Pleistocene, one of the intentions of this thesis, it is concluded that:

- The Saalian Stage comprises the Fennoscandian, British and Alpine glaciations of cycle C, corresponding to MIS 6, and evidence for two more glacial-interglacial cycles, MIS 10-9 and 8-7 respectively,
- The Holsteinian Stage can be assigned to MIS 11,
- The Elsterian Stage can be equated with MIS12,
- The 'Cromerian Complex' Stage comprises the Donian glaciation of cycle H in eastern Europe which corresponds to MIS 16. The positions of the Cromerian warm substages[8] are difficult to correlate with the marine sequence because of the fragmentary nature of its record.

The marine isotope stratigraphy cannot be defined as the yardstick for the terrestrial chronostratigraphy, it only forms a reference for the timing of the terrestrial climatic stages and events. The time-transgressive boundary levels of the stages lie within the range of the deglaciation intervals for which the terminations give indicative ages. The boundary levels at the MIS 12/11 - and MIS 16/15 transitions are proposed as lower stage boundaries for the late Middle Pleistocene and a subdivision of the early Middle Pleistocene into a part A and B, respectively.

The low-resolution event-stratigraphical framework is provisional and is intended to be an initiative towards a formal subdivision. The evidence, advocated to underpin and refine the terrestrial event-stratigraphical framework, is not straightforward and still faces the problems inherent to its fragmentary and heterogeneous nature. The criteria for identification and definition of genetic sequence and event-stratigraphical units, with large-scale correlation potential, need to be further developed. In many cases this will involve a reinvestigation and reinterpretion of known sites and sequences. Comparison of eastern and western European evidence will improve the understanding of the stratigraphical relationships. Moreover, a better insight can be obtained by including sedimentary facies analysis in geological investigation and classification. An additional aspect is the equipping of the event-stratigraphical schemes with a revised and unambiguous nomenclature and terminology.

Possibilities for further refinement of the timing of the interpreted palaeoclimatic events during the Middle Pleistocene lie in new evidence and techniques. They comprise the recognition of boundaries at clearly defined horizons from both the MIS and the terrestrial stratigraphies. Although it is well known that the terrestrial equivalents of the global scale deglaciation intervals in the MIS are time-transgressive within a range of thousands of years, reduction of the diachronity of the boundary levels may be achieved by research on the various 'lag' times of the geological and ecological responses of climatic change. To achieve this, local detailed records are essential for the timing of the periods intermediate of the large-scale events. New high-resolution information can be embedded/integrated as reference records in the terrestrial schemes with regard to local variability of climatic change and neotectonics which can then be equated with the global scale of the marine isotope record.

[1] *This, otherwise, had for long been a well understood reality.*

[2] *With the exception of the marine Noordbergum (= Cromerian IV) intercalation of which the stratigraphical position is unclear.*

[3] *Chronometric controls of the Laurentide Wisconsin glacial deposits in the USA indicate glacial advances during the time periods represented by the MIS 4 and MIS 2, as recorded by the southernmost extensions of end-morainesat various locations ranging between about 65-79 ka respectively 22-14 ka BP (Richmond & Fullerton 1986).*

[4] *Boundaries between thick loess beds and palaeosol complexes based by a B-horizon.*

[5] *And consequently for the absolute ages of many early Palaeolithic levels.*

[6] *Or 'sub-subseries'.*

[7] *Of Matuyama age.*

[8] *The Cromerian substages II, III and IV within the Brunhes Chron.*

EPILOGUE

The stratigraphical evidence and information involved in this thesis covers the published literature for the period until September 2005, when the manuscript was submitted for publication and public examination. New evidence, such as the discovery of flint artefacts within the Cromer Forest-bed-Formation at Pakefield in Norfolk (England), is not included (Parfitt *et al.* 2005)[1]. The findings of Palaeolithic material within warm-stage deposits containing *Mimomys savini* is the first of such kind in northern Europe. It implies that the earliest human occupation of northern Europe already would have taken place during the first substage (e) of MIS 15, or even during a warm isotope stage prior to MIS 16, centered at around 600 ka.

The flints artefacts at Pakefield are found in organic fine-grained channel fill and overbank deposits that are incised into marine, estuarine and fluvial sediments. These warm-stage deposits are unconformably overlain by glaciofluvial deposits (Corton Sands) and the Lowestoft Till synthem of Anglian (= MIS 12) age. They were originally correlated with similar deposits of the Cromerian stratotype at West Runton, 60 km to the northeast, on the basis of the occurrence of *Mimomys savini*, palynology and malacology. The authors assume that both sites are close in age, also confirmed by AAR evidence, and suggest an early Middle Pleistocene age. It is the special combination of *Mimomys savini* with the occurrence of large mammals such as *Hippopotamus amphibius*, *Megaloceros dawkinsi* and *Palaeoloxodon antiquus* that distinguishes the Pakefield sequence from that of West Runton, lacking these large mammals. The authors propose an older age for the Pakefield sequence and hence an earlier presence of humans, i.e. before MIS 16. Their arguments are the occurrence of *Mimomys pusillus*, which indicates a pre-Donian age, and a new lithostratigraphical interpretation of the overlying sedimentary sequence suggesting evidence for a glaciation cycle coinciding with MIS 16.

The marine sediments overlying the warm-stage sediments at West Runton, noted in this thesis, are thought to reflect a marine transgressional cycle in the Anglo-Dutch North Sea type region equivalent to MIS 13 or MIS 15 substage a. They do not contain *Mimomys savini* and post-date the Pakefield warm-stage sediments (Gibbard *et al.* 1991). The last appearance date of *Mimomys savini* would then just have overlapped the presence of *Hippopotamus* and *Palaeoloxodon antiquus* in the Pakefield sequence. The option that the Pakefield flints date from MIS 15 (substage e) cannot be excluded therefore. The precise stratigraphical position of both warm-stage sequences, however, remains unclear as yet.

Notwithstanding, the findings of flint artefacts at Pakefield in warm-stage deposits containing *Mimomys savini* does not necessarily contradict the conclusion made in this thesis that there is no sound evidence of early human occupation before c. 600,000 years ago. At least they confirm the proposed lowering of the age boundary for the ‘short chronology’ theory (*sensu* Roebroeks & Van Kolfschoten 1995) from 500,000 to 600,000 years ago.

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Kier van Gijssel werd geboren op 30 mei 1957 in Koekange. Zijn jeugd bracht hij door in Friesland. In 1976 behaalde hij zijn VWO-diploma aan het Drachtster Lyceum. Van 1976 tot 1984 studeerde hij fysische geografie aan de Universiteit van Amsterdam met als afstudeerrichting Kwartaire geologie en (peri-)glaciale geomorfologie. Na meer dan tien jaar onderzoekswerk te hebben verricht bij onder andere de Rijks Geologische Dienst in Haarlem en de Universiteit Leiden, werkt hij momenteel als GIS-specialist bij het Hoogheemraadschap Hollands Noorderkwartier in Edam.

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