A continent-wide framework for local and regional stratigraphies

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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 (4^{th} 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 ð^{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.*