A continent-wide framework for local and regional stratigraphies

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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:

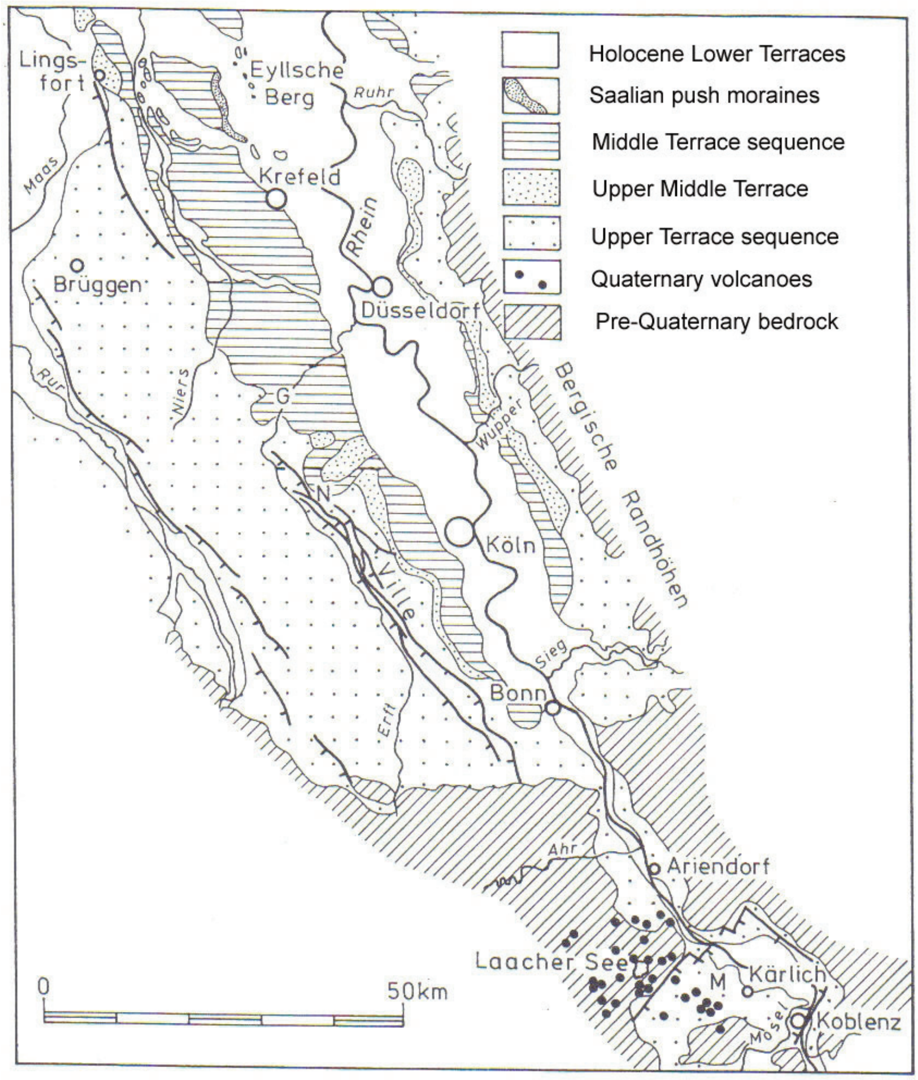


Figure 5.1: Kärlich and Ariendorf in the Middle Rhine region and the location of the terrace complexes along the river Rhine (Boenigk 1995). The Neuwied basin comprises a small (20x30 km) subsiding tectonic basin located in the centre of the Rhenish Shield.

- 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 nonglacial 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).

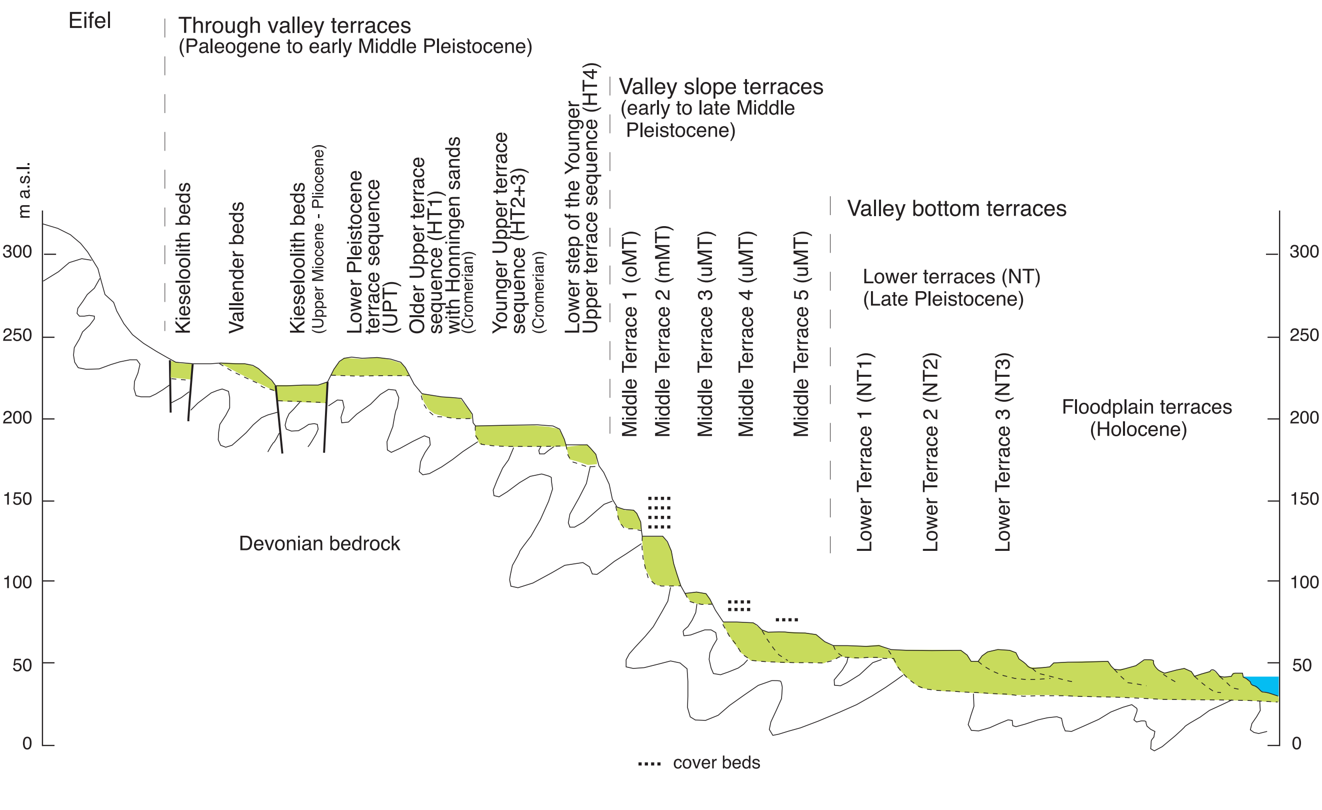


Figure 5.2: Schematic cross-section of the lower Middle Rhine valley (after Schirmer 1995) in which the subdivision and terminology of the terrace sequence is summarised and roughly ordered in time.

- *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-

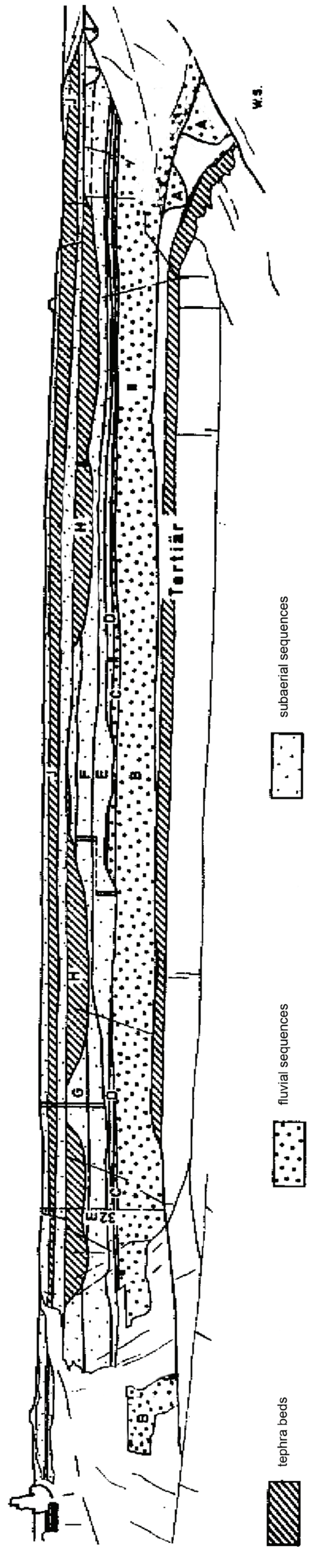


Figure 5.3: The classical Kärlich section (from Brunnacker *et al.* 1969).

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.

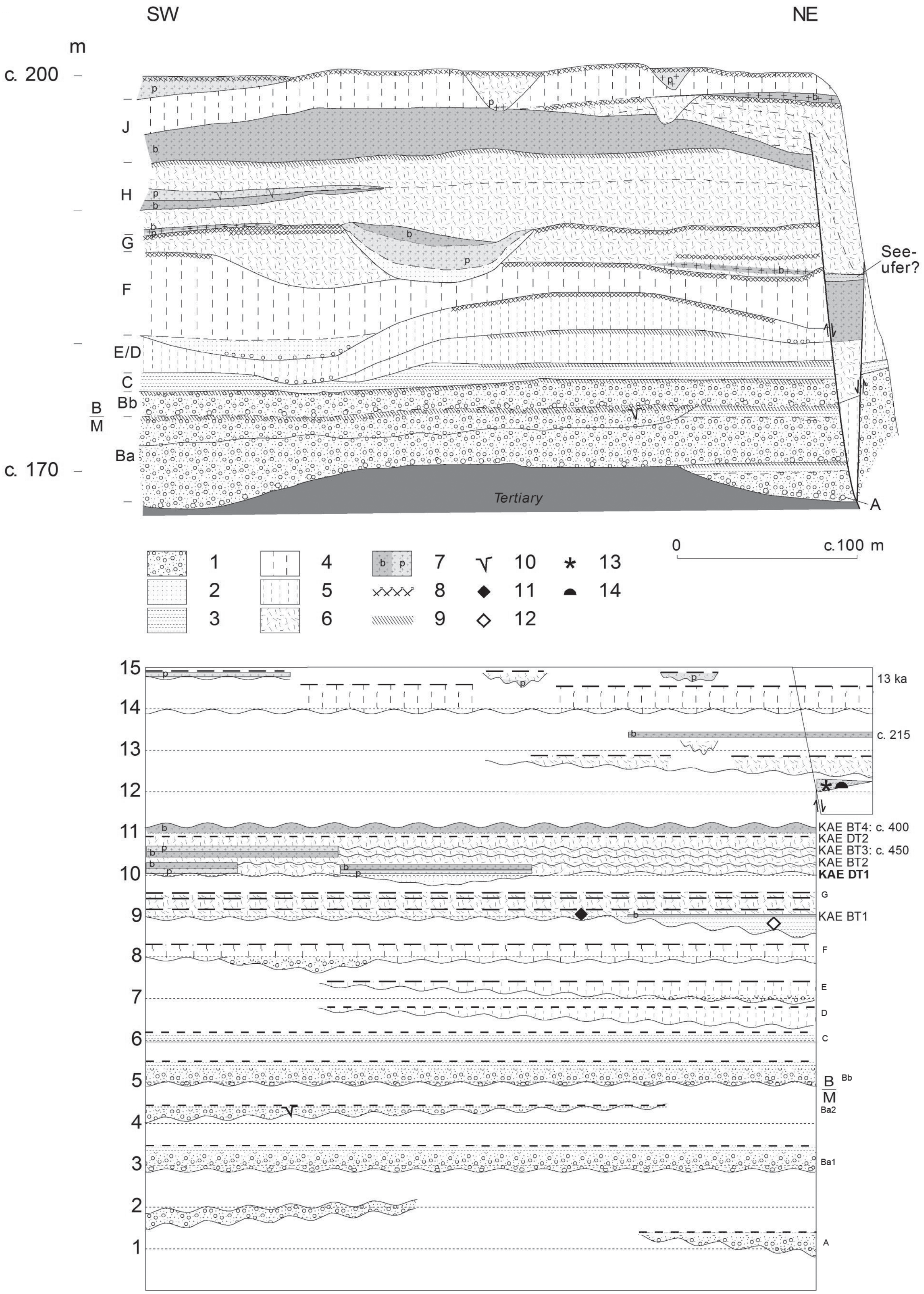


Figure 5.4: a) Lithostratigraphical model based on schematic section of Kärlich (Gaudzinsky *et al.* (1996); b) Interpreted chronostratigraphical model of the Kärlich section with unconformity-bounded sequence and containing bio- and chronostratigraphical information. 1) sand and gravel/ coarse-grained 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

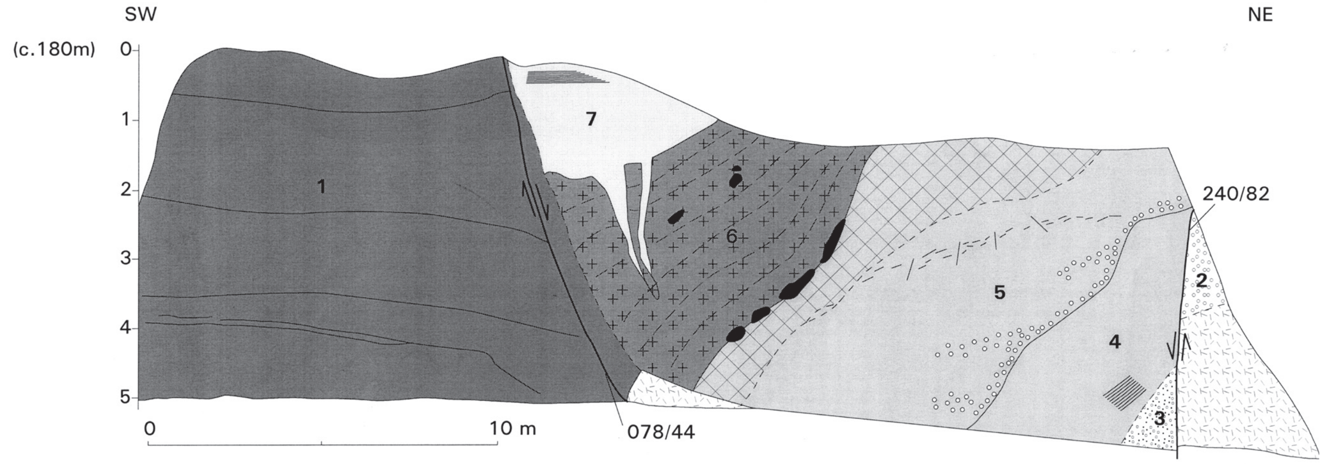


Figure 5.5: Section from a small outcrop near the Kärlich-Seeufer section close to the edge of the Rhine valley showing normal faults. 1. Tertiary clay ('Knubb'), 2. stratified sand and gravel, 3. sand and gravel (unit B?), 4. silt, partly laminated (unit C/D?), 5. silt with gravelly base ('Kieseloöliet'?) 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-

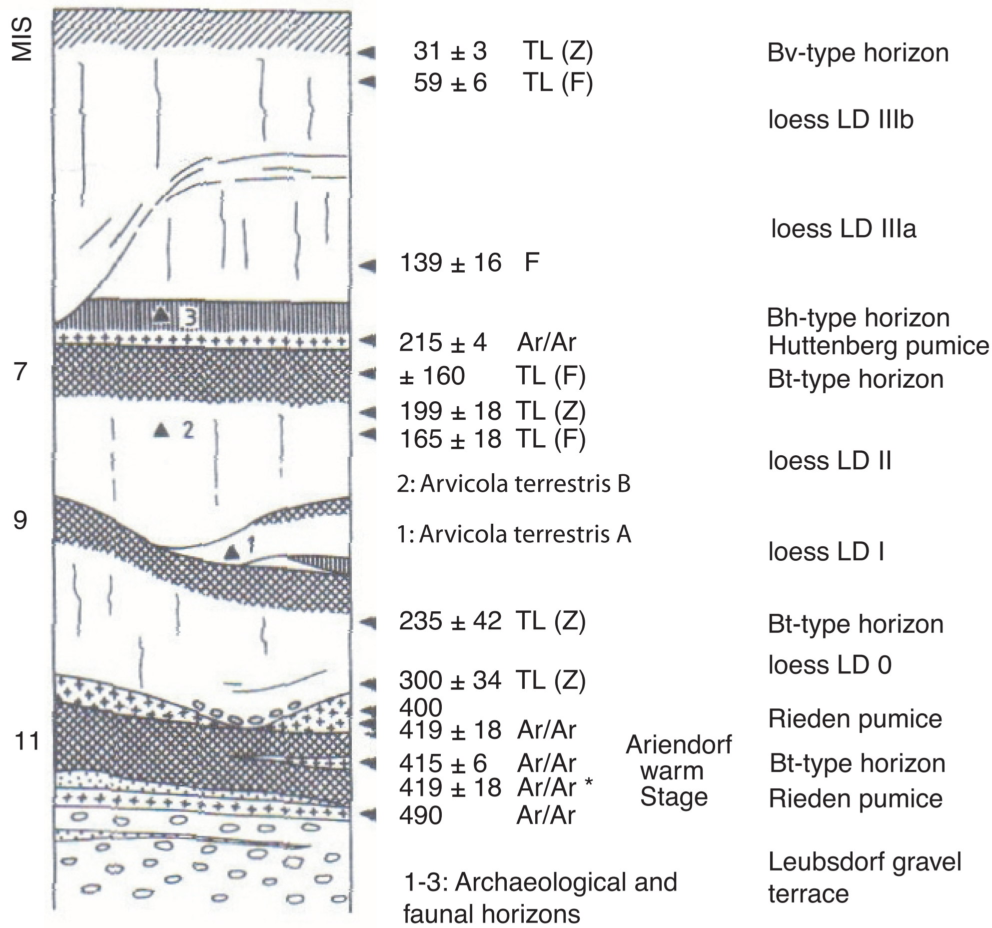


Figure 5.6: The Ariendorf section: stratigraphy, geochronological dates, faunal horizons and correlation of the fossil forest soils with the MIS (from Schirmer 1995). Ar/Ar dates by Van den Bogaard and Schminke (1990); Ar/Ar* date by Lippolt, Fuhrmann and Hradetsky (1986); F = Tl dating by Frechen (1993)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

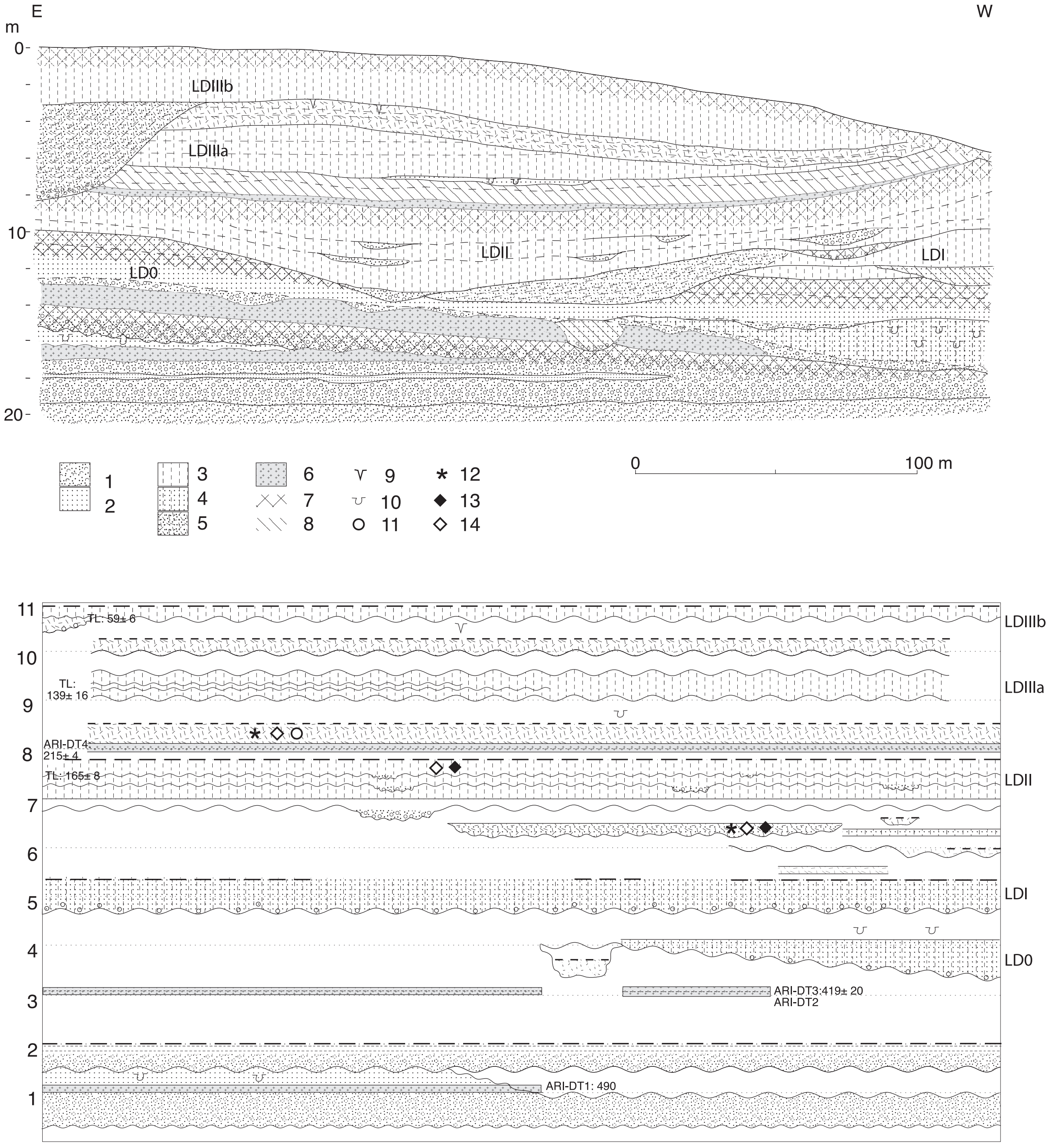


Figure 5.7: a) Lithostratigraphical model compiled from the schematic section of Ariendorf (after Haesaerts 1990; b) Interpreted chronostratigraphical model of the Kärlich section with unconformity-bounded sequence units and containing bio- and chronostratigraphical information. 1) sand and gravel/ coarse-grained 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.

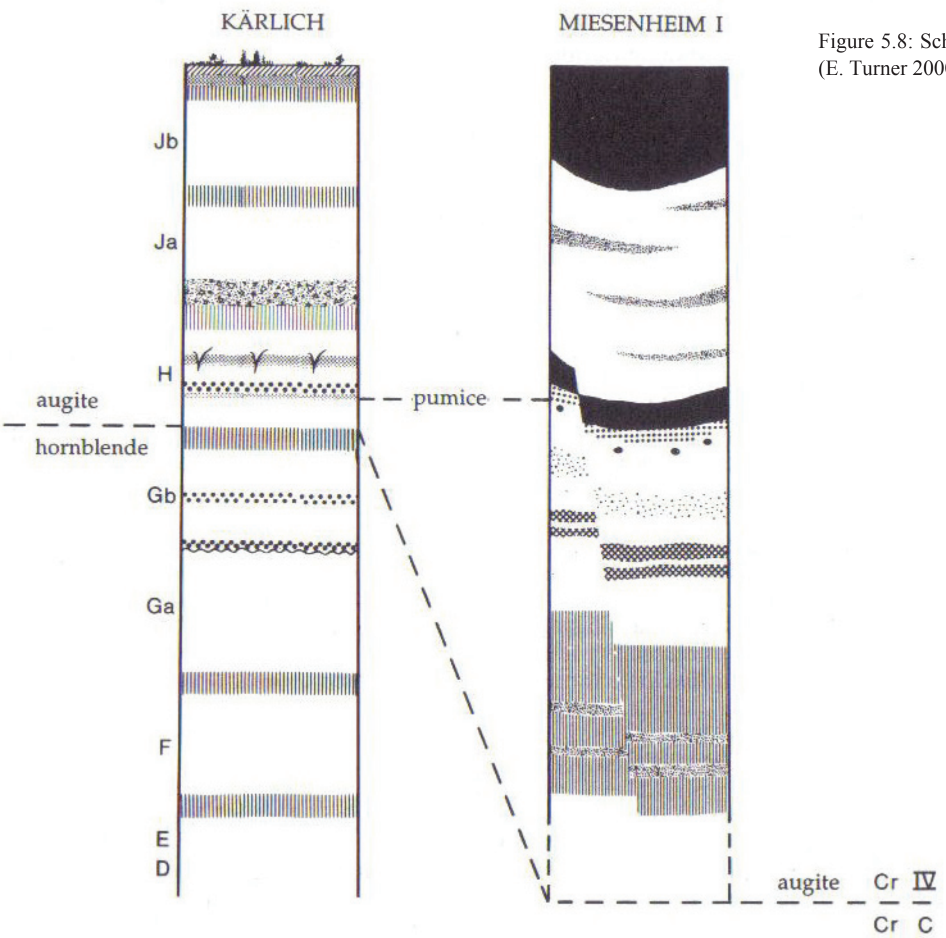


Figure 5.8: Schematic section of the Miesenheim I section (E. Turner 2000).

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

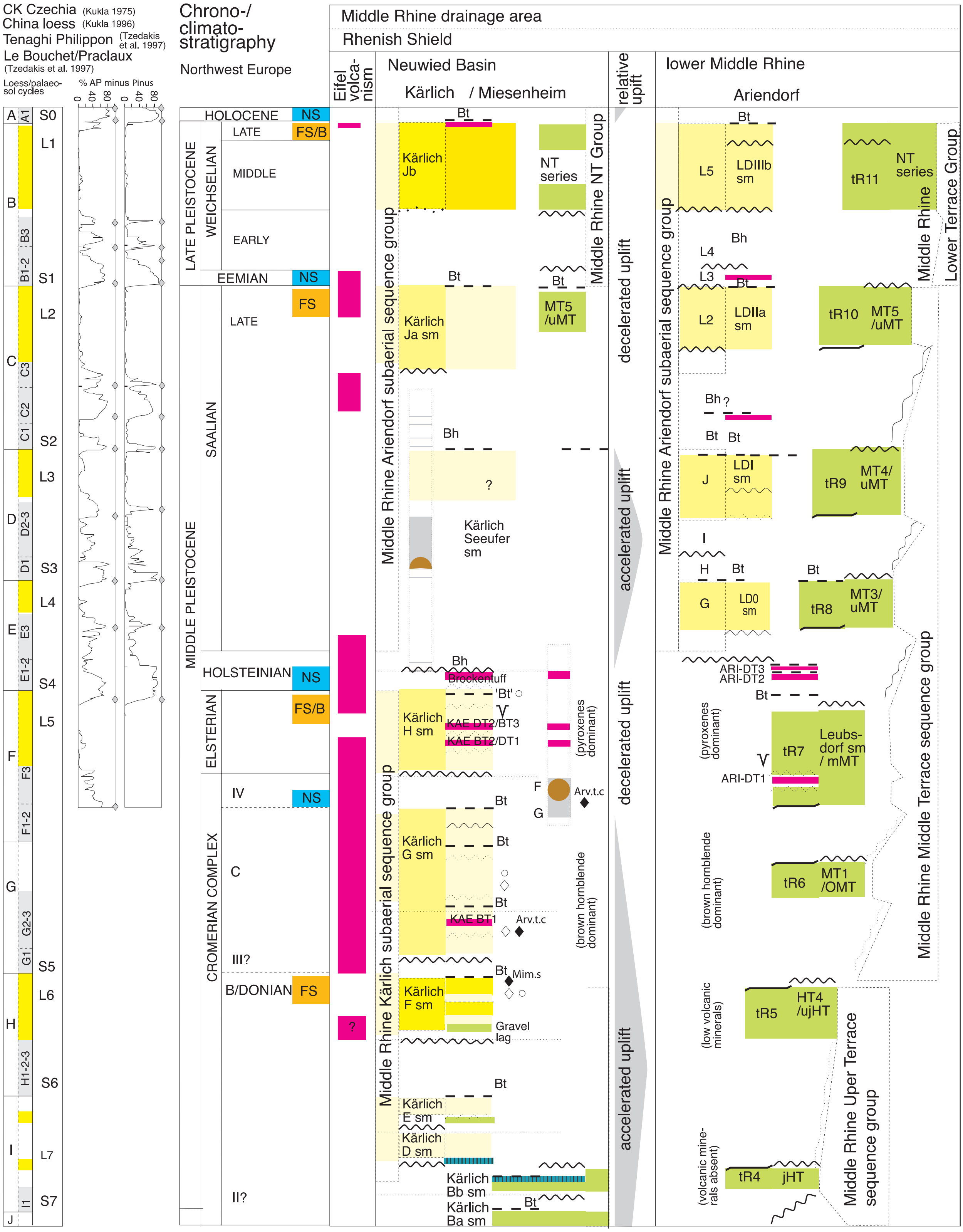
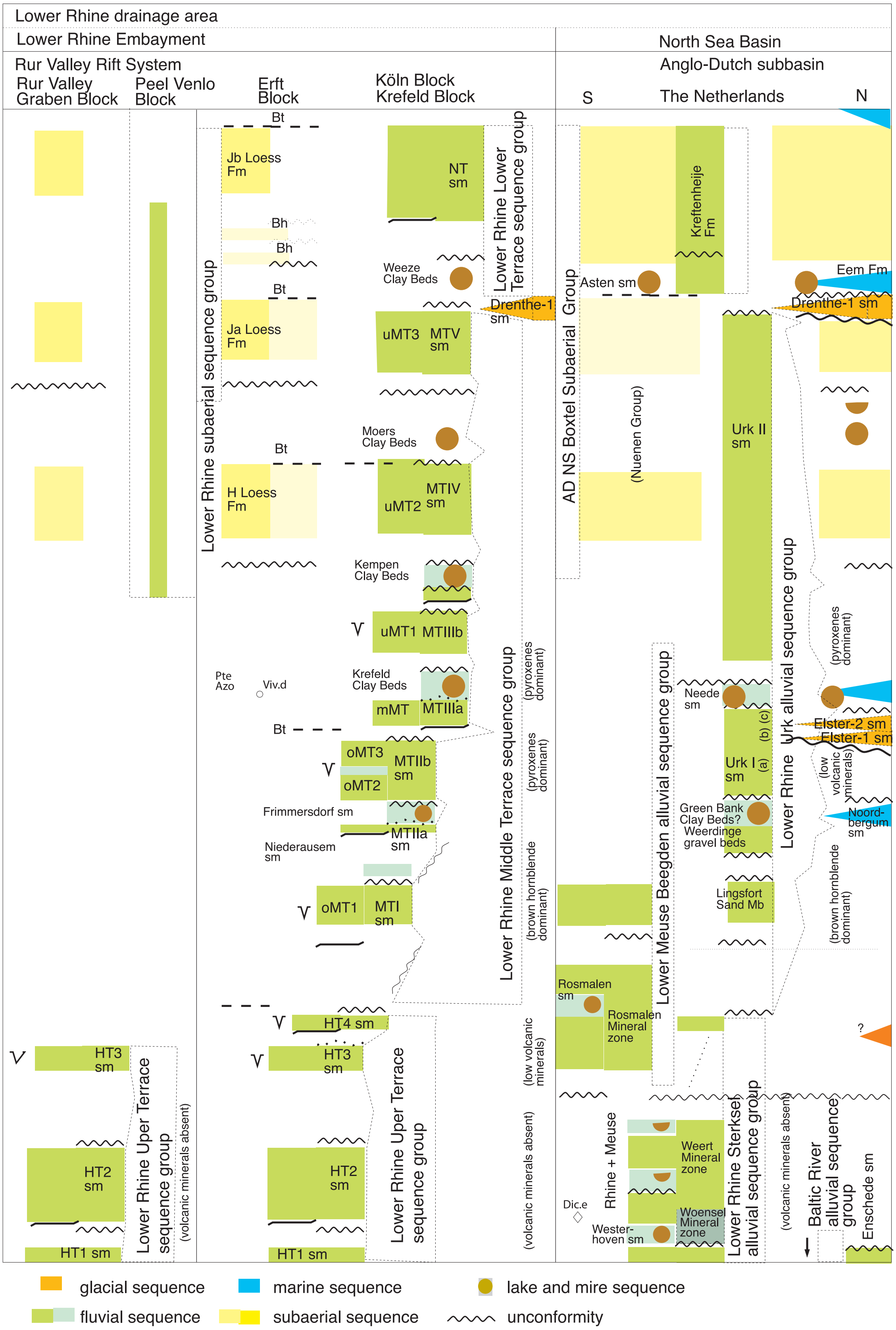


Figure 5.9: Correlation scheme of the Middle and Late Pleistocene genetic sequences for the Middle Rhine -, Lower Rhine Embayment - and Anglo-Dutch North Sea type areas. Compiled of data from Boenigk 1995, Boenigk and Frechen 2001, Brunnacker *et al.* 1969, Van den Bogaard & Schminke 1990, Schirmer 1990,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


Lower Rhine drainage area
Lower Rhine Embayment
North Sea Basin
Rur Valley Rift System
Anglo-Dutch subbasin
Rur Valley Graben Block
Peel Venlo Block
Erft Block
Köln Block
Krefeld Block
S
The Netherlands
N
Bt
Jb Loess Fm
NT sm
Bh
Bh
Weeze Clay Beds
Lower Rhine Lower Terrace sequence group
Kreftenheije Fm
Asten sm
Eem Fm
Bt
Ja Loess Fm
Drenthe-1 sm
Drenthe-1 sm
uMT3 MTV sm
AD NS Boxtel Subaerial Group
(Nuenen Group)
Lower Rhine subaerial sequence group
Moers Clay Beds
Urk II sm
Bt
H Loess Fm
MTIV sm
uMT2
Kempen Clay Beds
uMT1 MTIIIb
Lower Rhine Urk alluvial sequence group
(pyroxenes dominant)
(pyroxenes dominant)
Pte Azo
Viv.d
Krefeld Clay Beds
mMT MTIIIa
Neede sm
Lower Meuse Beegden alluvial sequence group
Bt
Elster-2 sm
Elster-1 sm
oMT3 MTIIb sm
oMT2
Lower Rhine Middle Terrace sequence group
(pyroxenes dominant)
(b) (c)
Urk I (a) sm
(low volcanic minerals)
Frimmersdorf sm
Green Bank Clay Beds?
Weerdinge gravel beds
Noord-bergum sm
MTIIa sm
Niederausem sm
(brown hornblende dominant)
(brown hornblende dominant)
Lingsfort Sand Mb
oMT1 MTI sm
Rosmalen sm
Rosmalen Mineral zone
HT4 sm
?
HT3 sm
HT3 sm
(low volcanic minerals)
Lower Rhine Uper Terrace sequence group
Lower Rhine Uper Terrace sequence group
(volcanic minerals absent)
(volcanic minerals absent)
(volcanic minerals absent)
Rhine + Meuse
Weert Mineral zone
Lower Rhine Sterksel alluvial sequence group
Baltic River alluvial sequence group
Enschede sm
HT2 sm
HT2 sm
Dic.e
Woensel Mineral zone
Wester-hoven sm
HT1 sm
HT1 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 (Boenigk)	Lower Rhine Basin (Boenigk)	Netherlands (Ebbing *et al.* 1999)	Netherlands (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

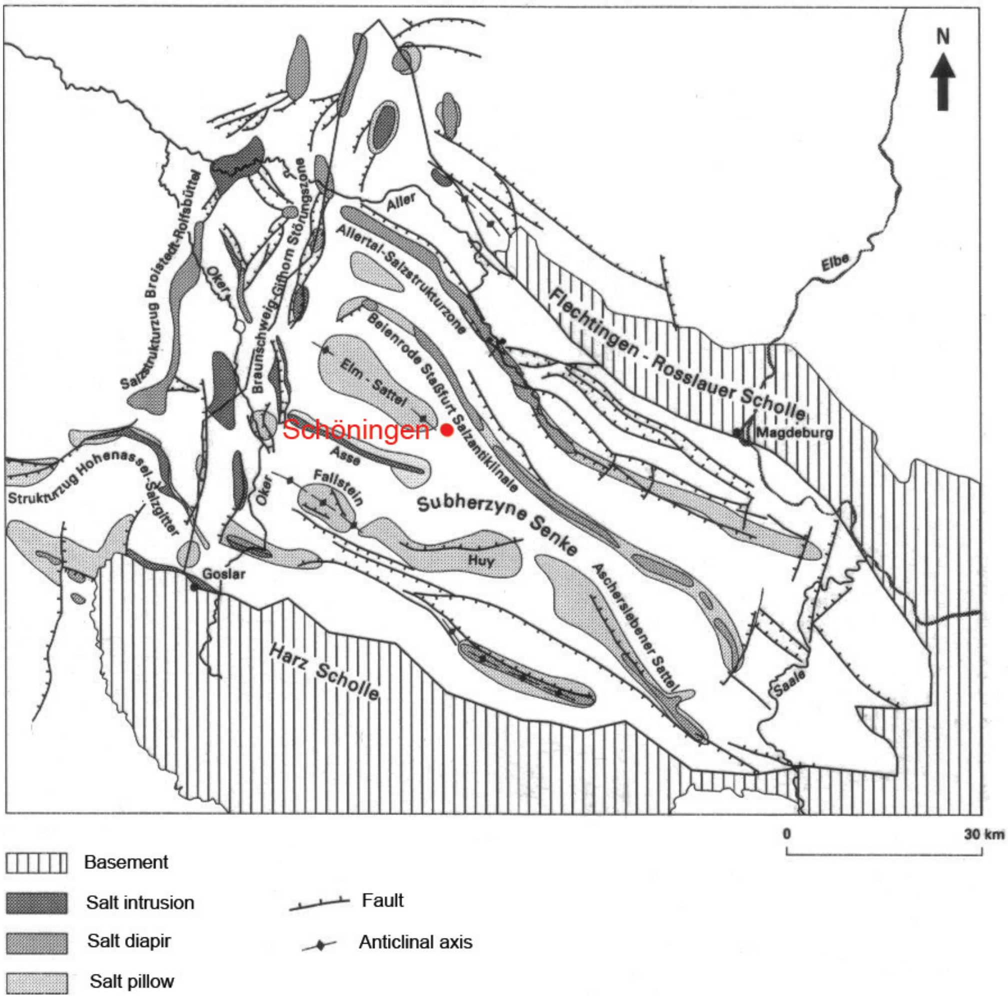


Figure 5.11: Location map of the Schöningen sections in the Subhercynic basin.

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.

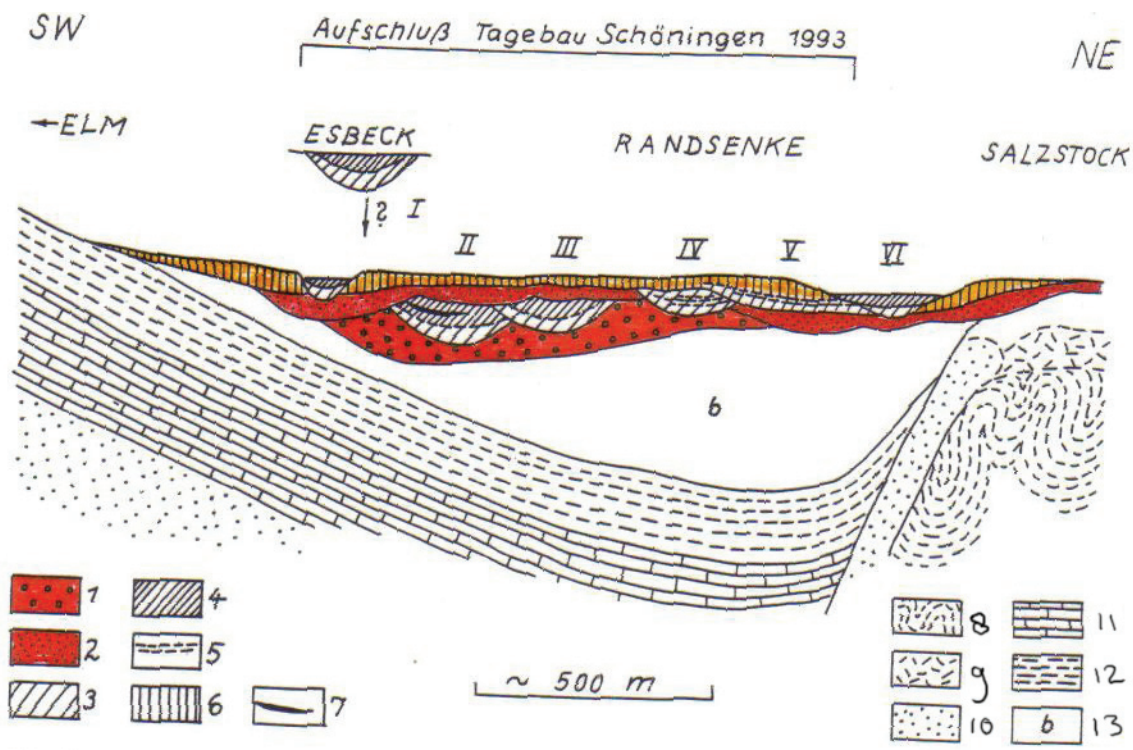


Figure 5.12: Schematic geological cross-section of the Schöningen open-cast mine in the western part of the rim syncline of the Beiersrode-Helmstedt-Staßfurt salt structure (Mania 1993). 1. Elsterian glacial sequence, 2. Saalian glacial sequence, 3. subaerial sequence, 4. lake and mire sequence, 5. soil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

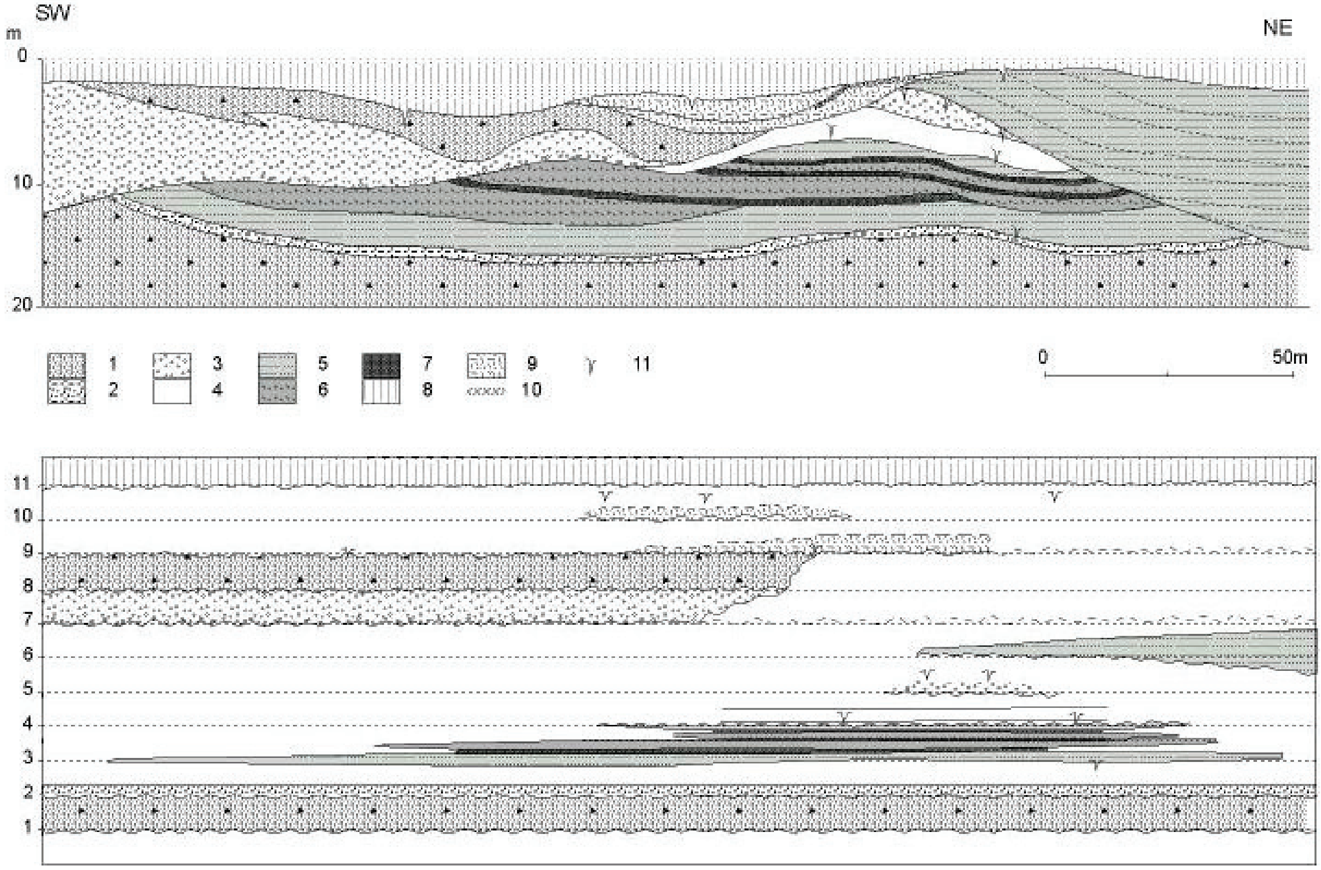


Figure 5.13: a) Lithostratigraphical and b) chronostratigraphical models based on schematic SW-NE section of Schöningen 12B by Thieme *et al.* 1993. 1. till, 2. gravel, 3. sand and gravel, 4. sand, 5. fine sand and silt, 6. clayey silt and mud (lake marl), gyttja, 7. peat, 8. loess, 9. loess derivates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

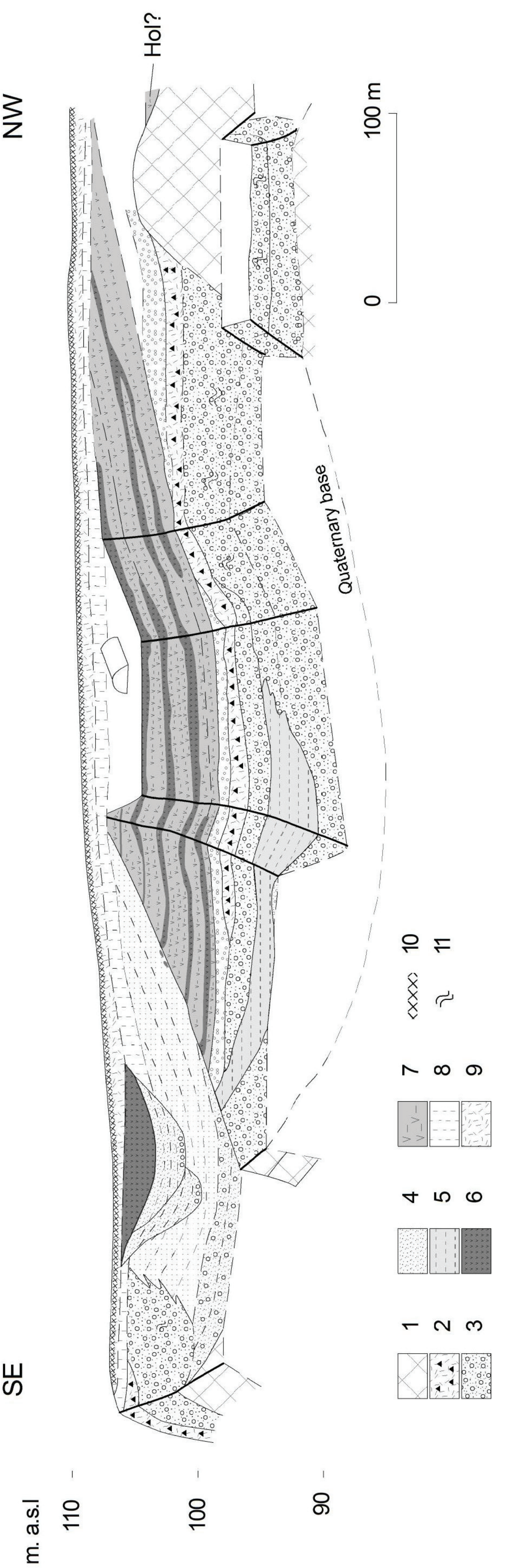


Figure 5.14: Schematic overview of the SE-NW section of Schöningen 13. 1. Tertiary clay, 2.till, 3. sand and gravel, 4. fine sand and silt, 5. fine sand and silt (glaciolacustrine), 6. peat, 7. clayey silt and mud (lake marl), gyttja, 8. loess, 9. loess derivates, 10. soil complex, 11. deformation structures.

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 (4^{th} 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-

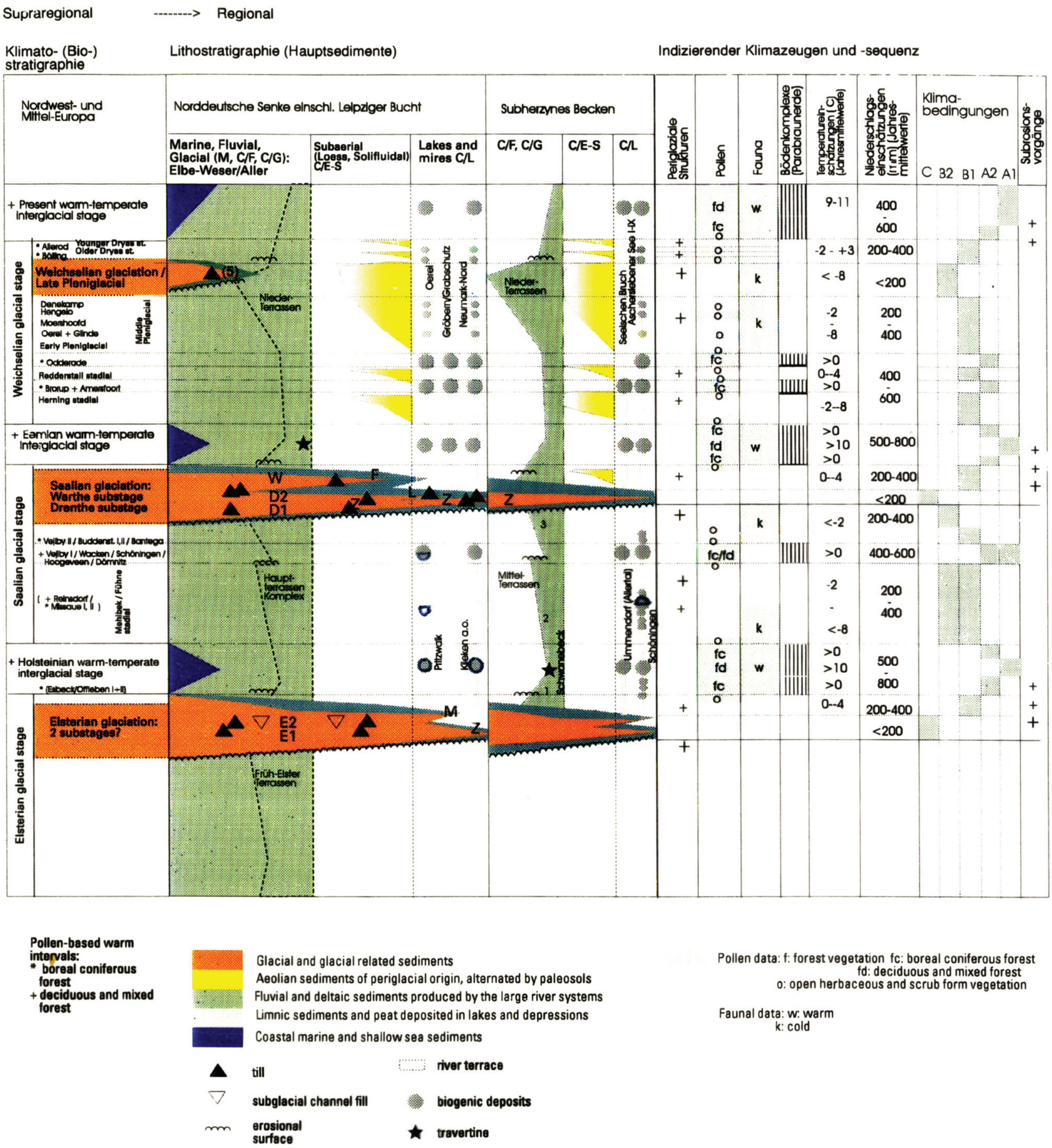


Figure 5.15: Stratigraphical correlation scheme of the late Middle and Late Pleistocene for the Subhercynic Basin and the southern part of the North German North Sea subbasin.

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.*