A continent-wide framework for local and regional stratigraphies

Gijssel, K. van

Chapter 4

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

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

4.1 Main natural type regions of Northwest and Central Europe

4.1.1 Geotectonic type regions

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

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

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

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

4.1.2 Distribution of Pleistocene sediments

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

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

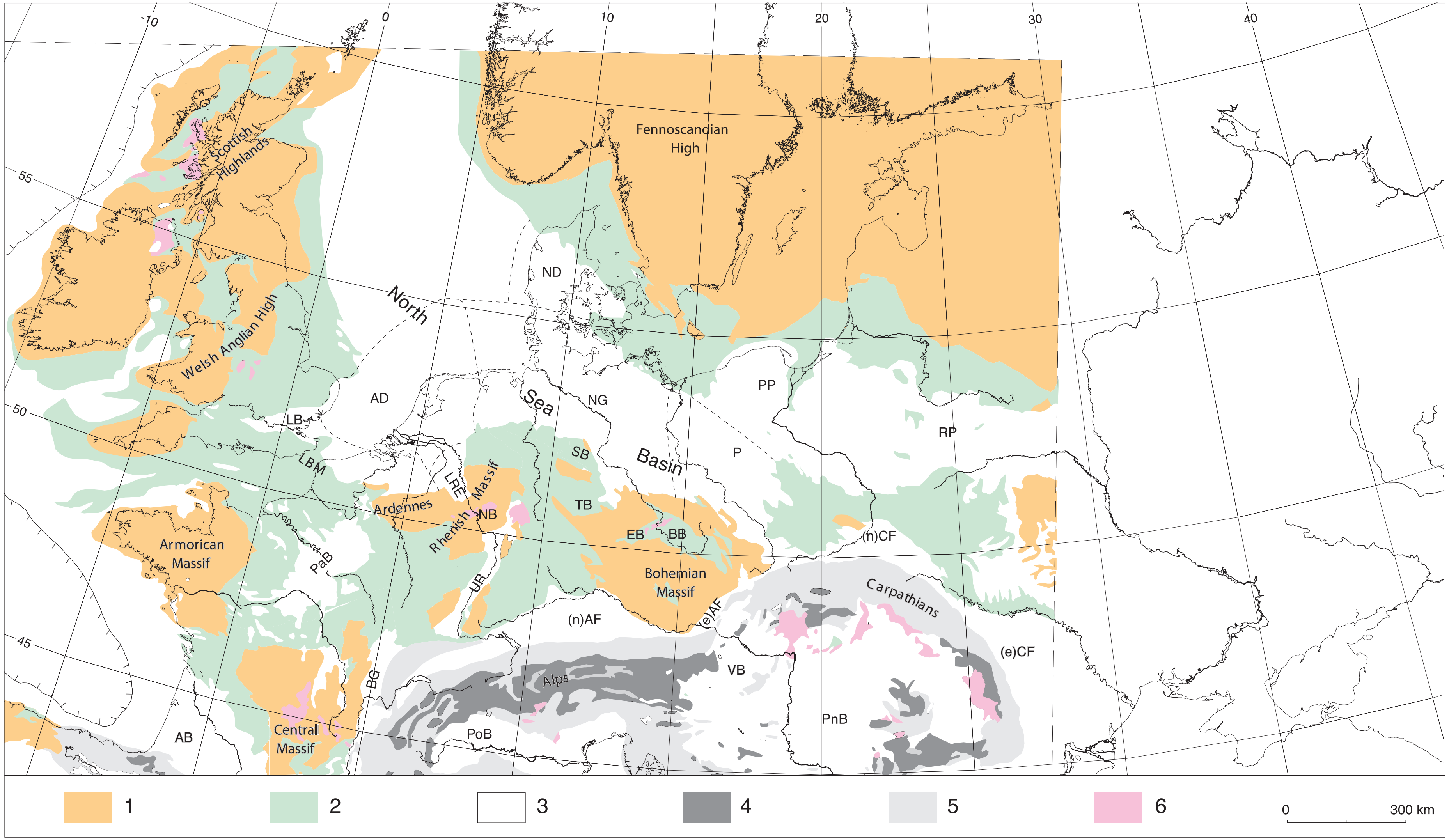


Figure 4.1 Location map showing the main geotectonic type regions in Northwest and Central Europe featuring Mesozoic and Cenozoic large- and medium-scale sedimentary basins (from Geological Map of Europe, BGR/Unesco). 1. Precambrian, 2. Mesozoic, 3. Cenozoic basins and sub-basins, 4. Alpine orogenic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

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

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

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

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

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

4.2.1 Wide-spread unconformity-bounded units and genetic sequences

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

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

[a] Glacial synthems and sequences

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

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

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

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

[b] Subaerial loess synthems and sequences

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

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

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

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

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

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

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

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

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

4.2.2 Regional-scale unconformity-bounded units and genetic sequences

[a] Fluvial synthems and sequences

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

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

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

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

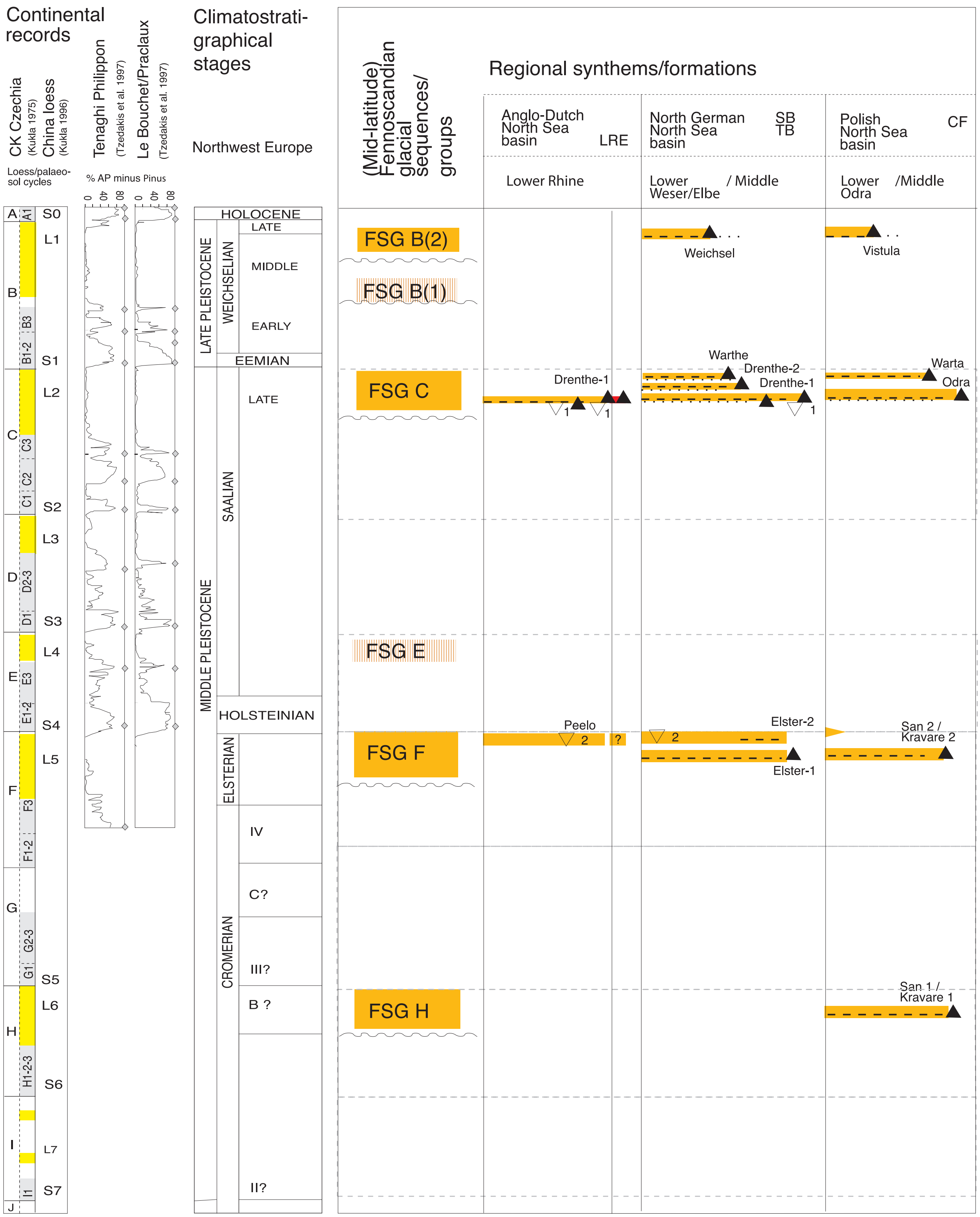


Figure 4.2 Continent-wide and regional subdivision of Middle and Late Pleistocene glacial synthems and sequences for Northwest and Central Europe. Nomenclature is tentative and largely follows existing unit names.

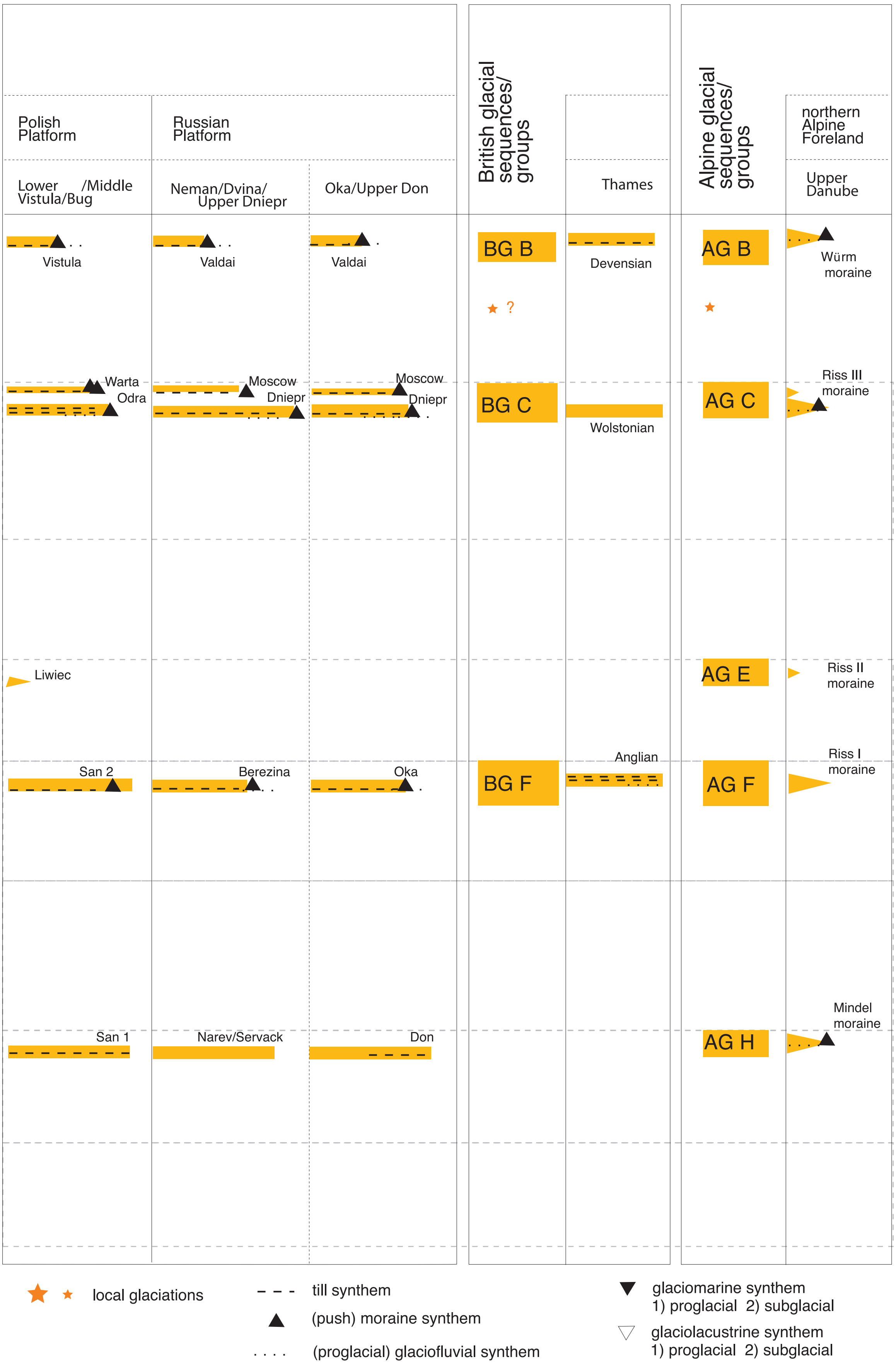
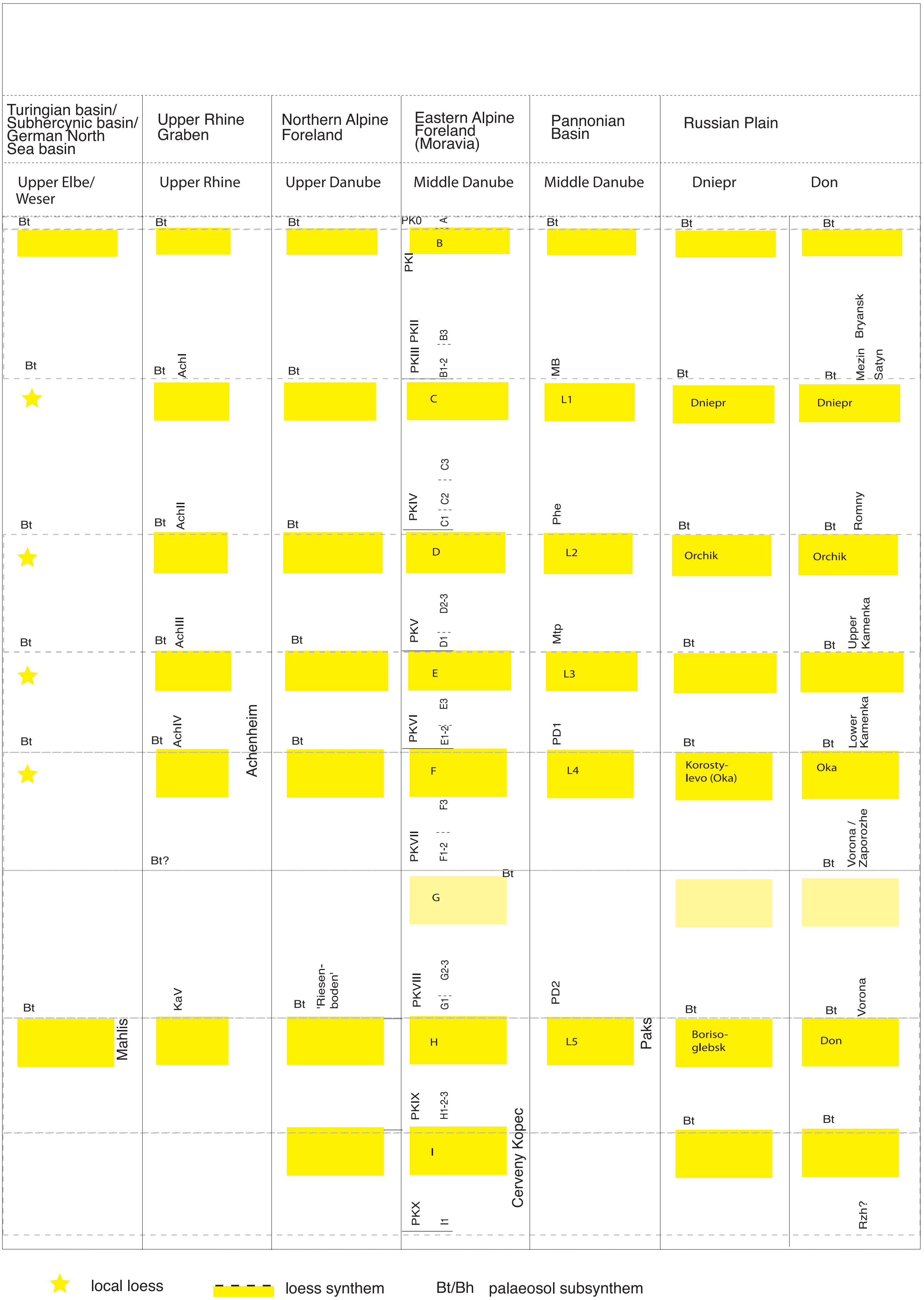

Polish Platform
Russian Platform
British glacial sequences/ groups
Alpine glacial sequences/ groups
northern Alpine Foreland
Lower /Middle Vistula/Bug
Neman/Dvina/ Upper Dniepr
Oka/Upper Don
Thames
Upper Danube
Vistula
Valdai
Valdai
BG B
Devensian
AG B
Würm moraine
?
Warta
Odra
Moscow
Dniepr
Moscow
Dniepr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

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



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

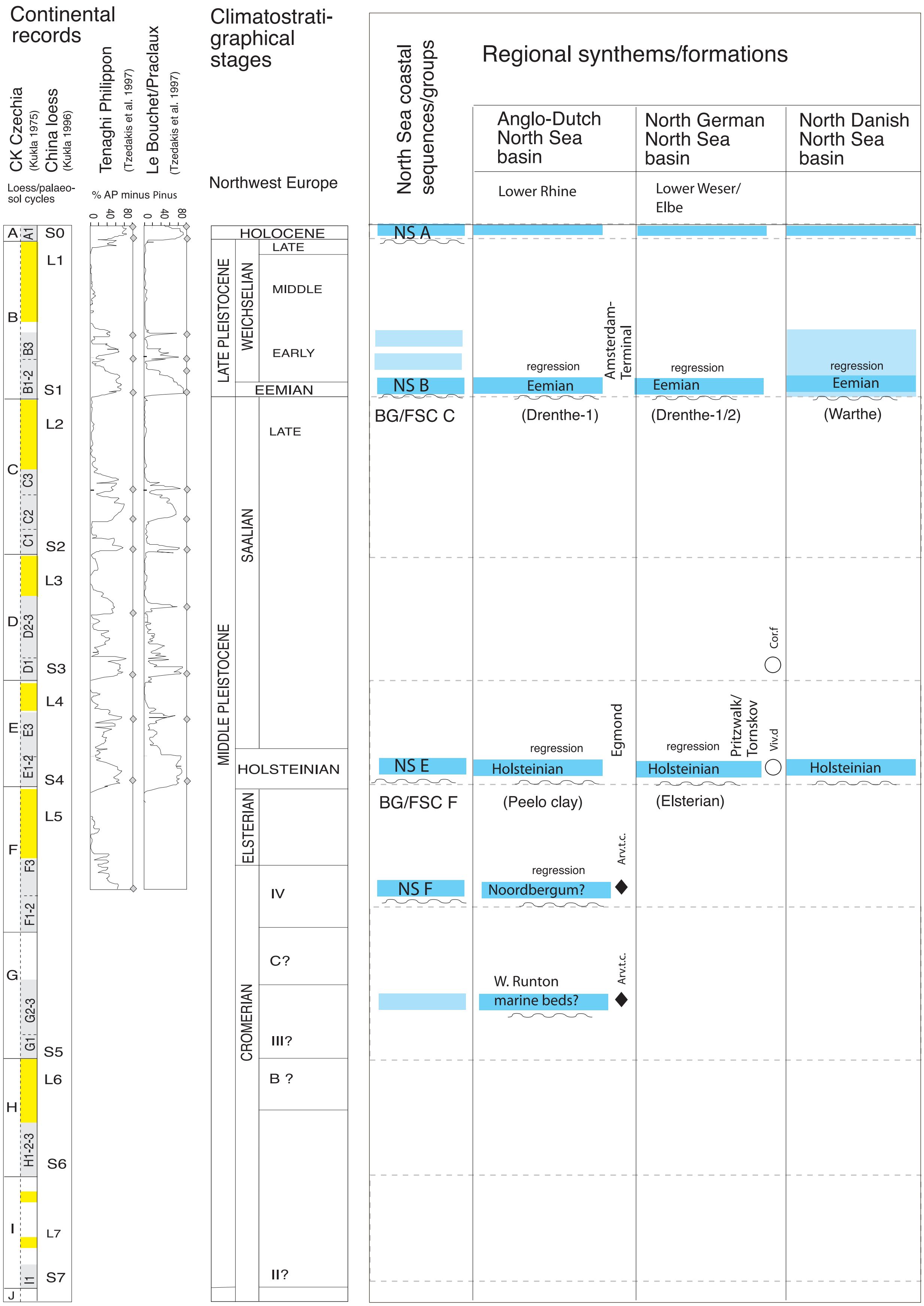
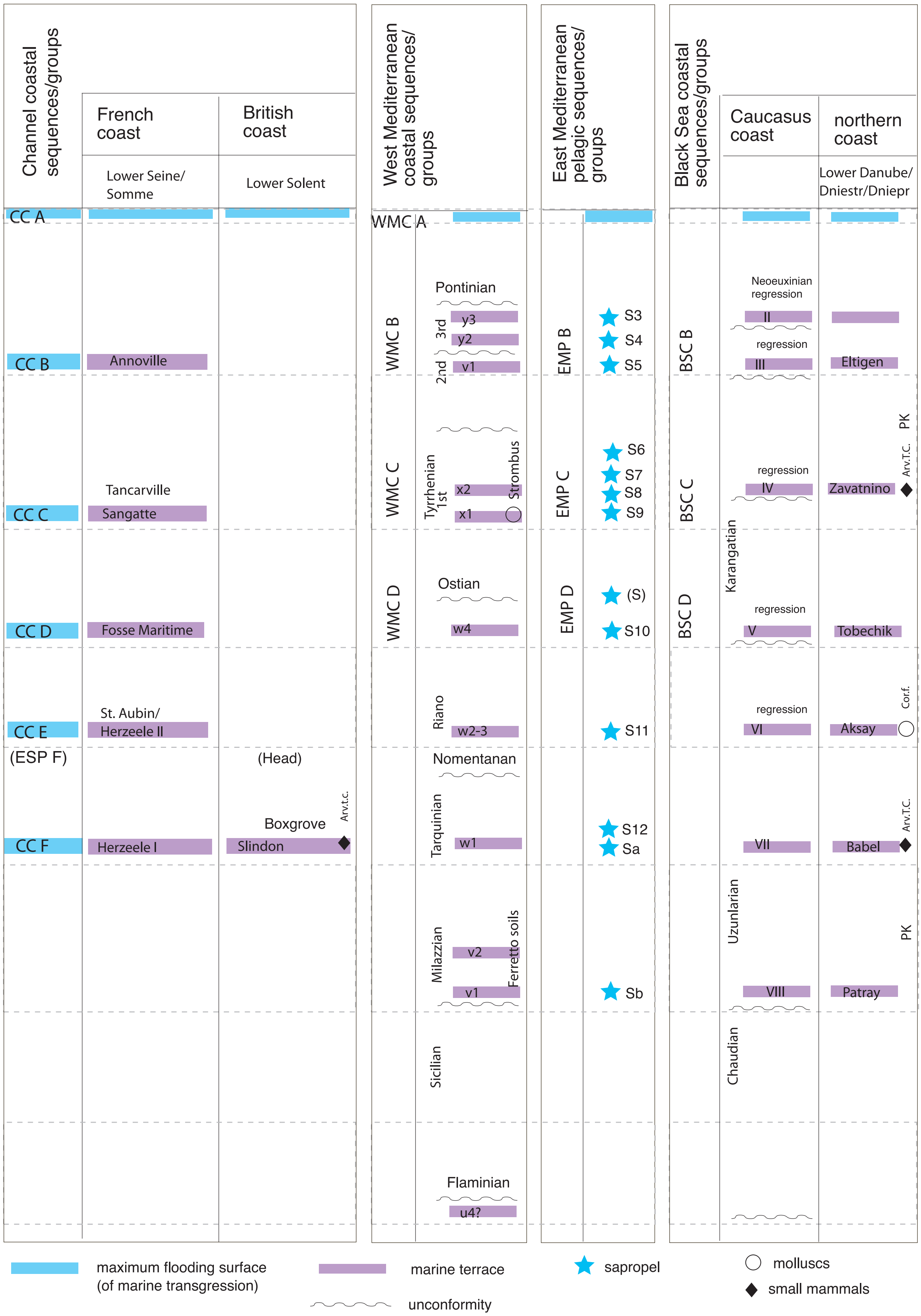


Figure 4.4 Continent-wide and regional subdivision of Middle and Late Pleistocene marine synthems and sequences for Northwest and Central Europe. Nomenclature is tentative and largely follows existing unit names.



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

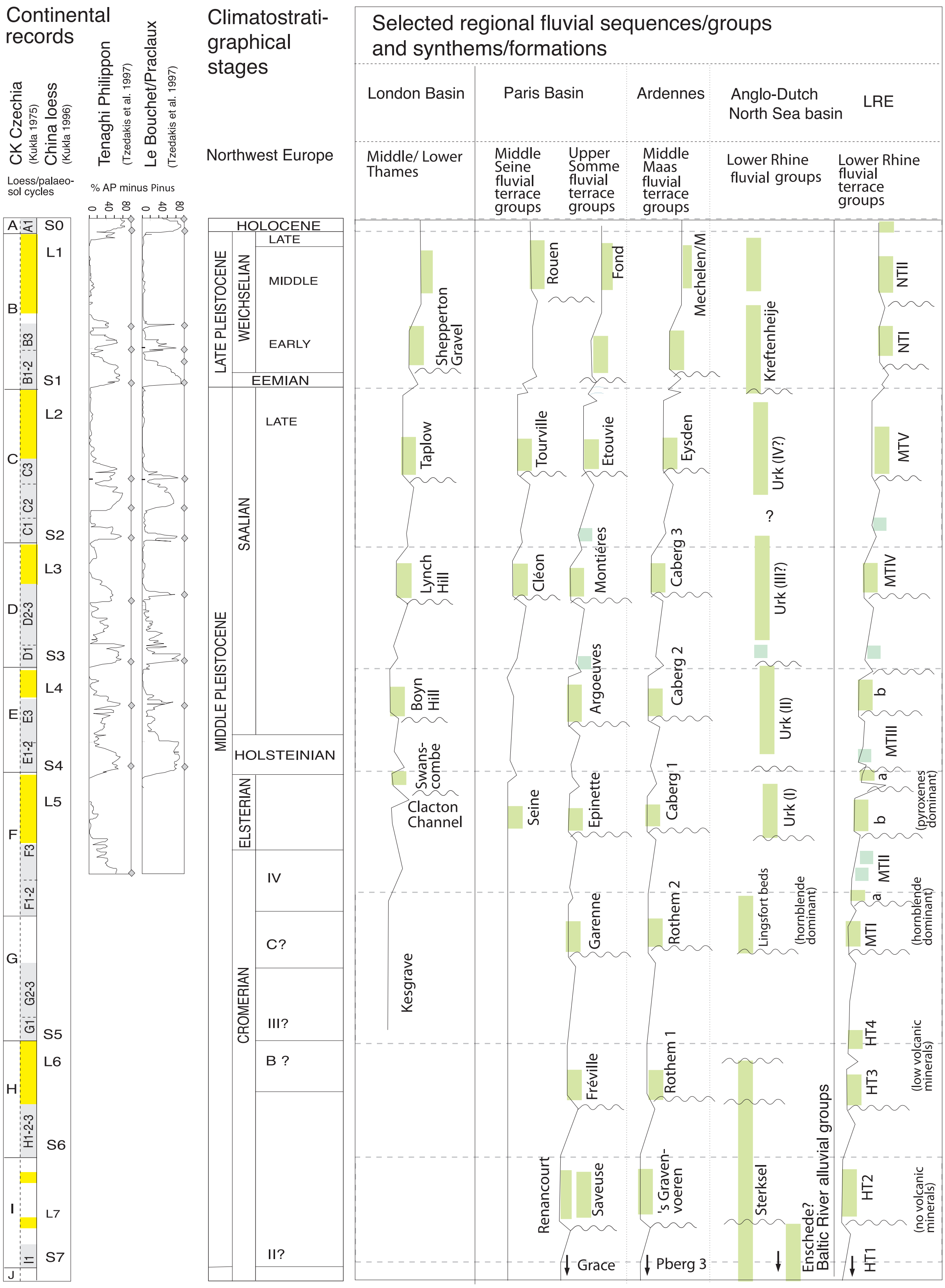
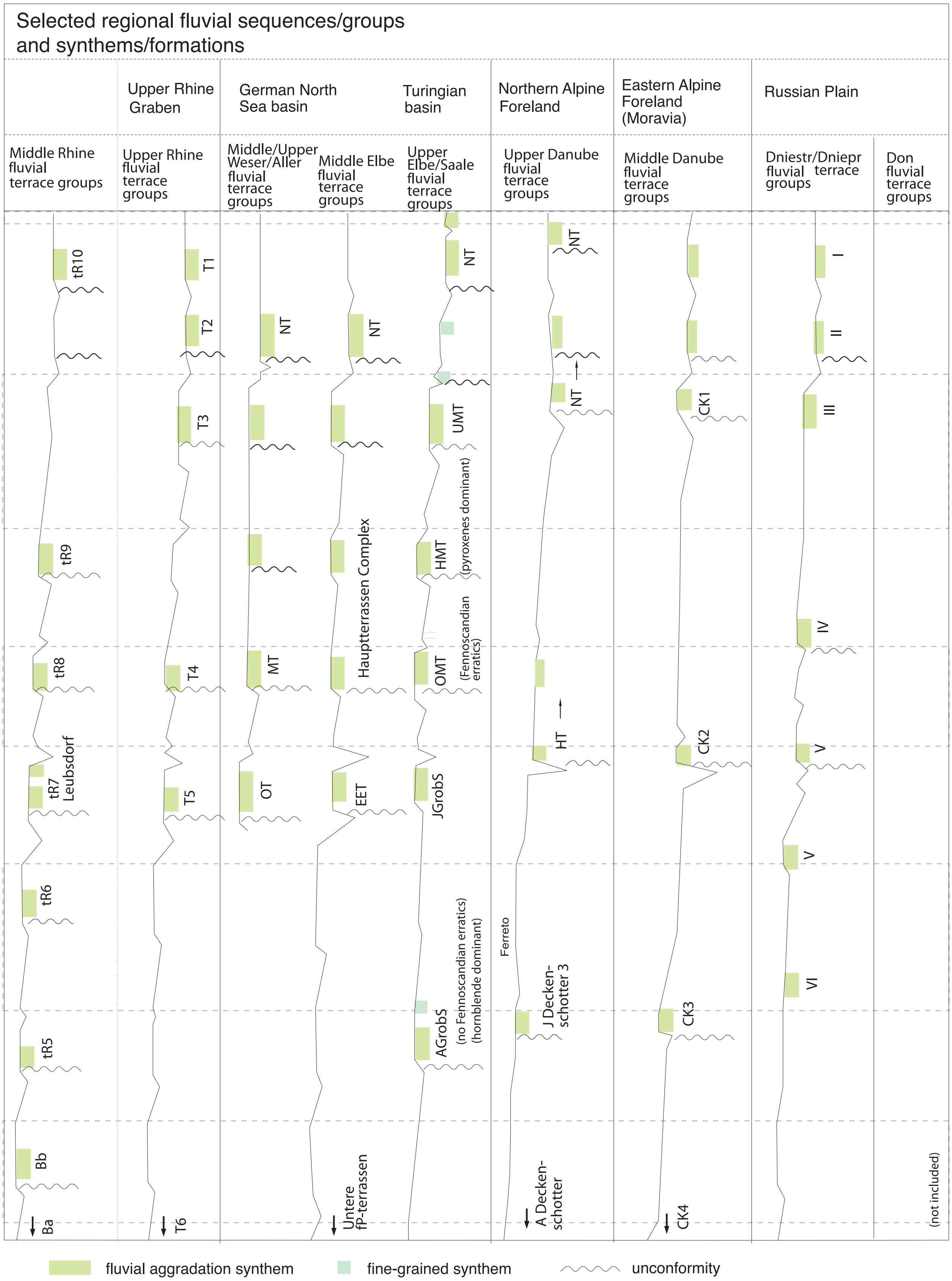


Figure 4.5 Continent-wide and regional subdivision of Middle and Late Pleistocene fluvial synthems and sequences for Northwest and Central Europe. Nomenclature is tentative and largely follows existing unit names


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

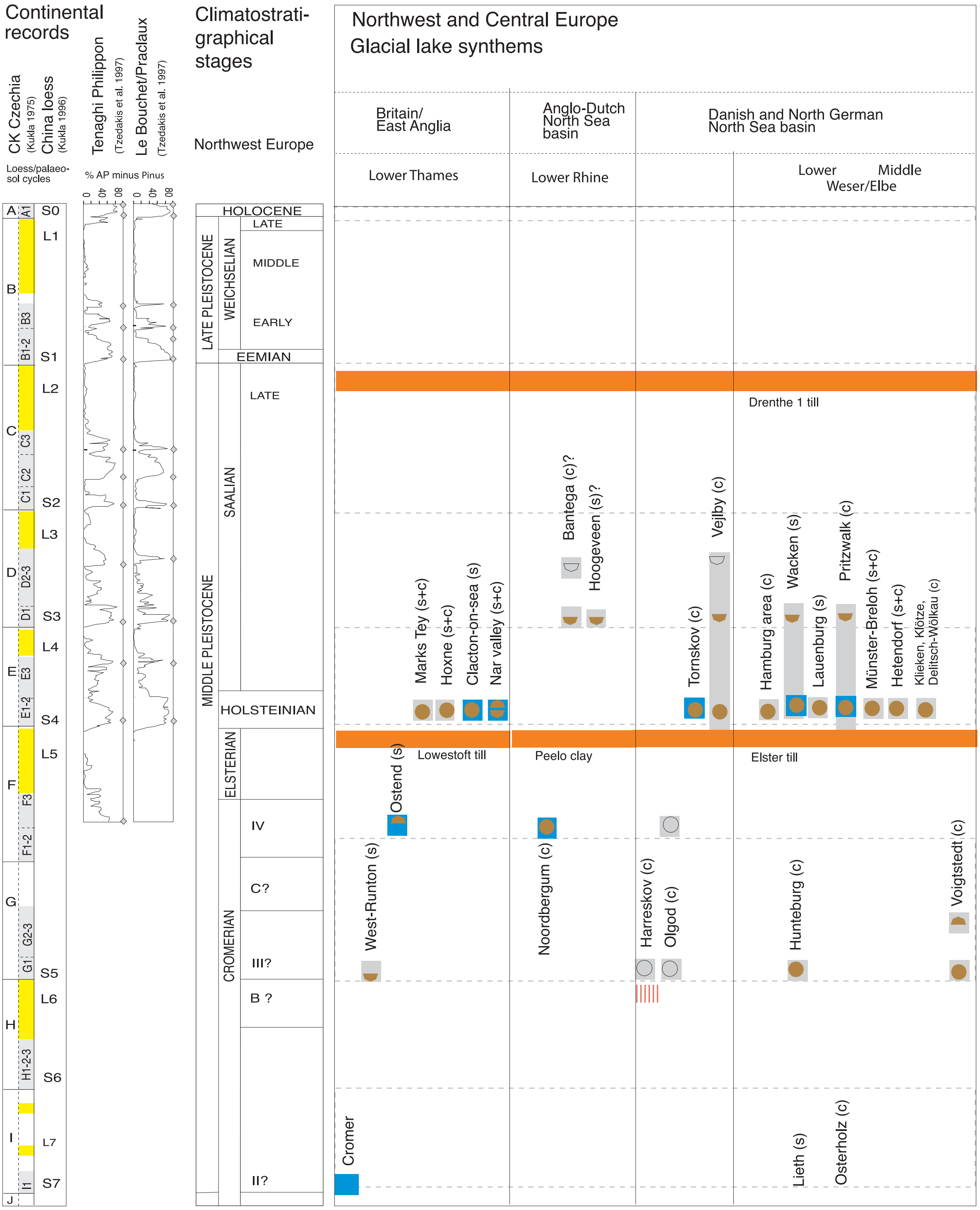
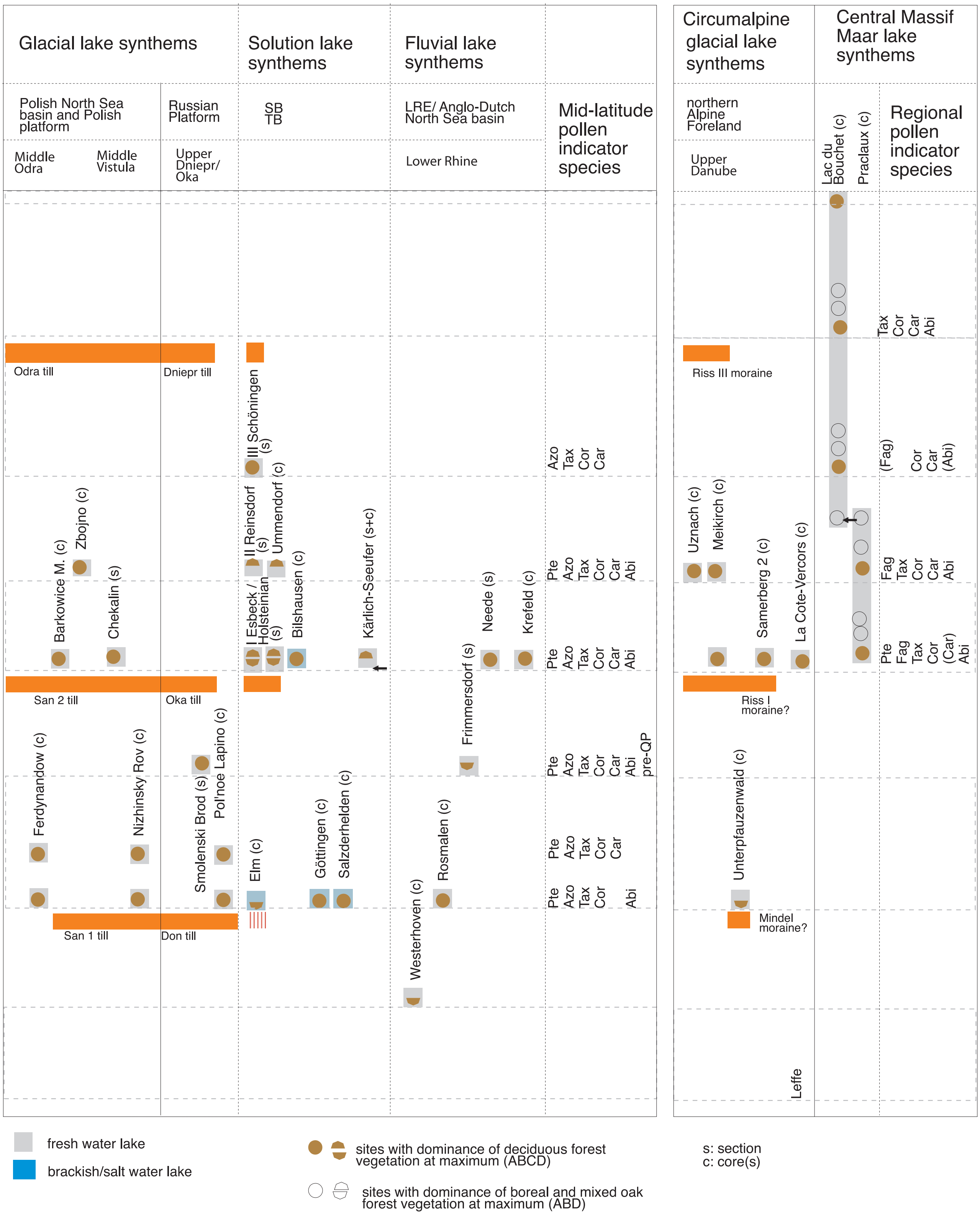


Figure 4.6 Continent wide and regional subdivision of selected Middle Pleistocene lacustrine synthems and sequences for Northwest and Central Europe. Nomenclature is tentative and largely follows existing unit names


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

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

[b] Subaerial non-aeolian synthems and sequences

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

4.2.3 Local-scale unconformity-bounded units and genetic sequences

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

[a] Lake and mire synthems and sequences

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

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

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

[b] Other sequences from terrestrial (sub)environments

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

4.3 Interregional correlation of the land-based Middle Pleistocene sequences

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

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

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

4.3.1 Glacial stratigraphy of Northwest (and Central) Europe

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

[a] The glacial sequence within the Saalian Stage

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

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

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

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

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

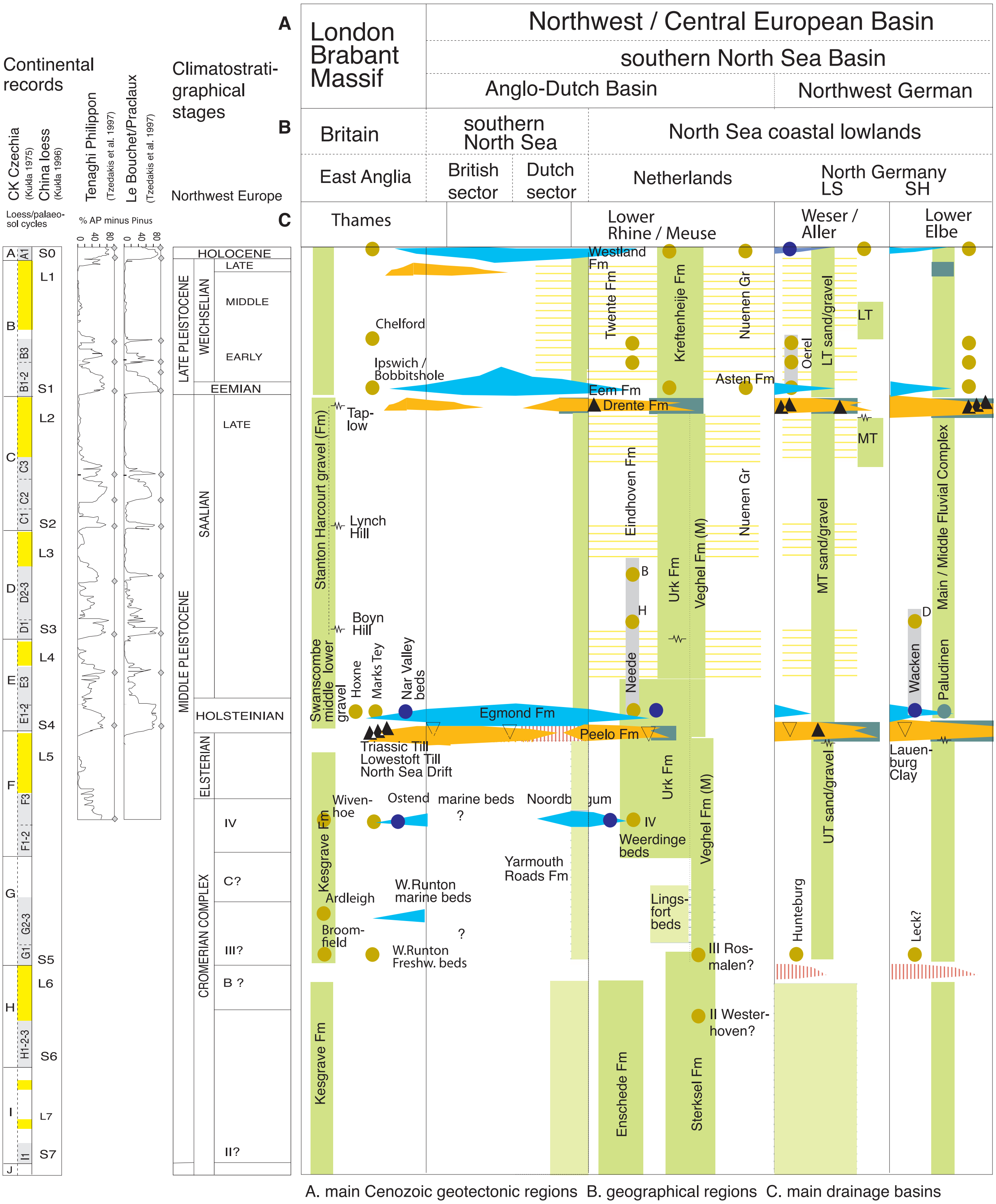
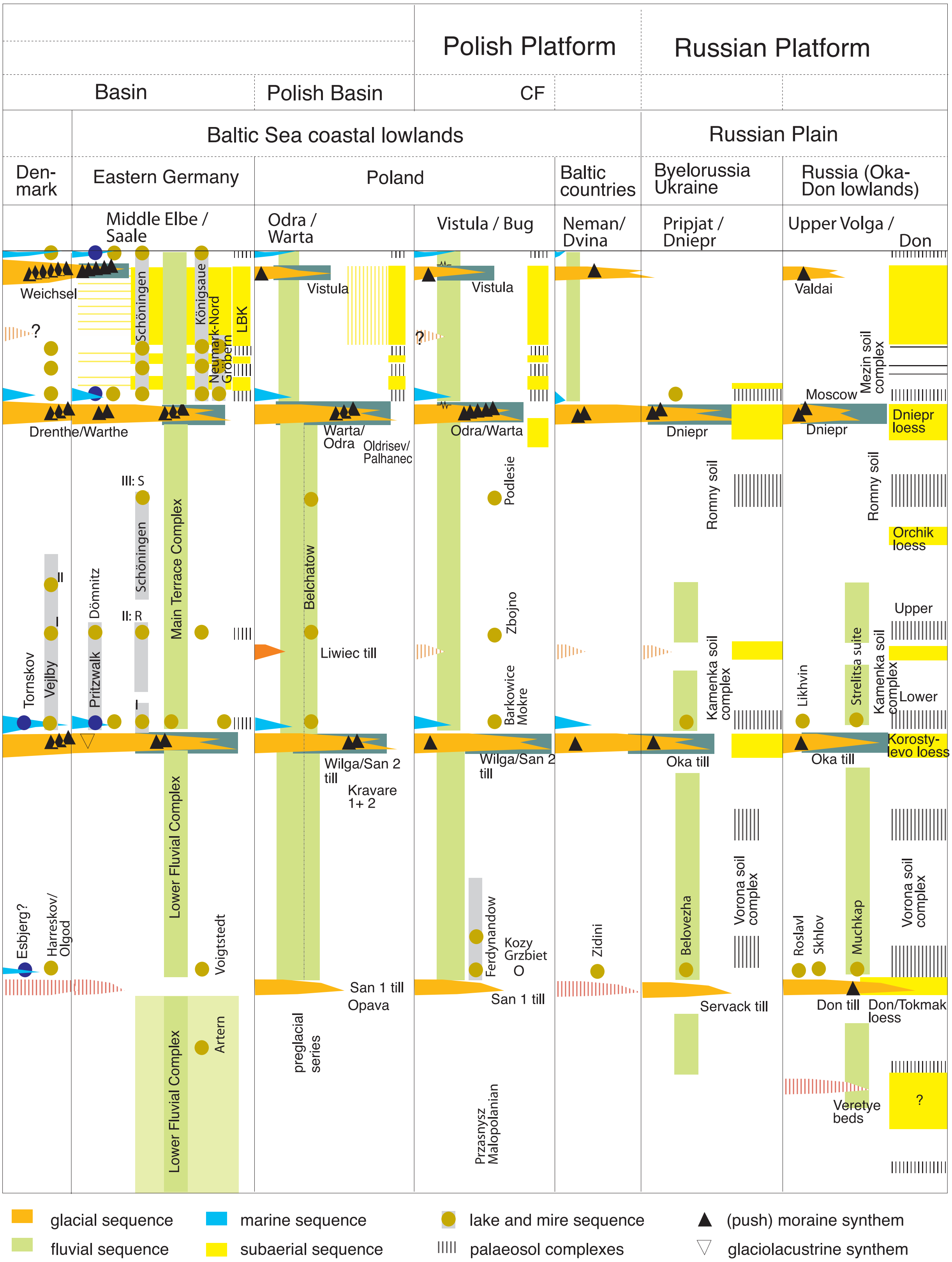


Figure 4.7 Middle and Late Pleistocene genetic sequence stratigraphy for the glaciated areas in Northwest and Central Europe.


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

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

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

[c] The Holsteinian temperate Stage

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

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

[d] The Elsterian cold Stage

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

[e] The'Cromerian Complex' Stage

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

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

4.3.2 Fluvial terrace and loess stratigraphy of Central Europe

[a] Loess stratigraphy

The loess units in *Figure 4.3* and *Figure 4.8* in the extraglacial upland areas are generally located in river valleys and tectonic basins. They occur as spatially separated sequences within their type regions overlying river terrace deposits. Only in eastern Europe are loess sequences traceable over large areas. Next to primary loess, the sequences in many type areas include loess derivates and slope wash deposits. On a temporal scale the different loess units are separated by warm-climate palaeosol complexes and bounded by erosional unconformities.
Loess/palaeosol sequences are associated with global-scale glacial-interglacial climatic cycles. They are best documented in the subaerial loess/palaeosol key sections of Eurasia of which the China loess record (Kukla 1987) is shown as a reference. They have their counterparts in the terrace sequences in the uplands of Central and Northwest Europe. The most complete regional loess terrace stratigraphies are those of Červený Kopec (eastern Alpine Foreland), Kärlich and Ariendorf (Middle Rhine), Achenheim (Upper Rhine Graben) and St. Pierre-les-Elbeufs (Paris Basin).

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

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

[b] Fluvial terrace stratigraphy

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

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

The terrace sediment bodies in the upland areas, separated by lateral unconformities, also are grouped into upper, middle and lower terrace complexes but on morphostratigraphical grounds. They are distinguished by clear changes in the basal erosion levels and comprise several coarse-grained lithofacies units associated with cold climate aggradation (*section 4.2.2*).
The erosional break from the middle terrace to the lower terrace complexes in the North German type areas coincides with the break in Central European loess cycle C from terrace *CK2* to *CK1* and the transition in the northern Alpine Foreland from the Hochterrassen to the Niederterrassen within the Rissian-Würmian Complex.
The base of the upper terrace complexes, predating the first (Elsterian) glacial sequence in the Elbe area ('*Frühelsterterrasse*': lacking erratic glacial material), features the deepest incision phase in the type area. A similar extremely incised valley is present in the Lower Rhine Embayment underlying the base of the *Middle Terrace IIIa* sediments or the '*Rinnenschotter*' (*section 5.3*). The heavy-mineral composition of the sand and gravel filling of the latter is dominated by pyroxenes, of which the first occurrence is dated about 500-450 ka, as are the alluvial sediments of the downstream AD/NS Urk I alluvial sequence group which are unconformably overlain by glacial sediments of the Elsterian glaciation. This striking erosional unconformity prior to the Elsterian glaciation is also found in terrace sediment systems of the middle and upper sections of the Rhine, Elbe and Danube rivers, beyond the glaciated areas. It corresponds with the break from *CK3* to *CK2* in the upper Danube Morava sub-basin (cycle F). Another conspicuous, anomalous morphological variation in the erosion base levels of the above-mentioned river systems, coinciding with the change from the *CK4* terrace to the *CK3* terrace during cycle H, is discussed in *section 4.4.3*.

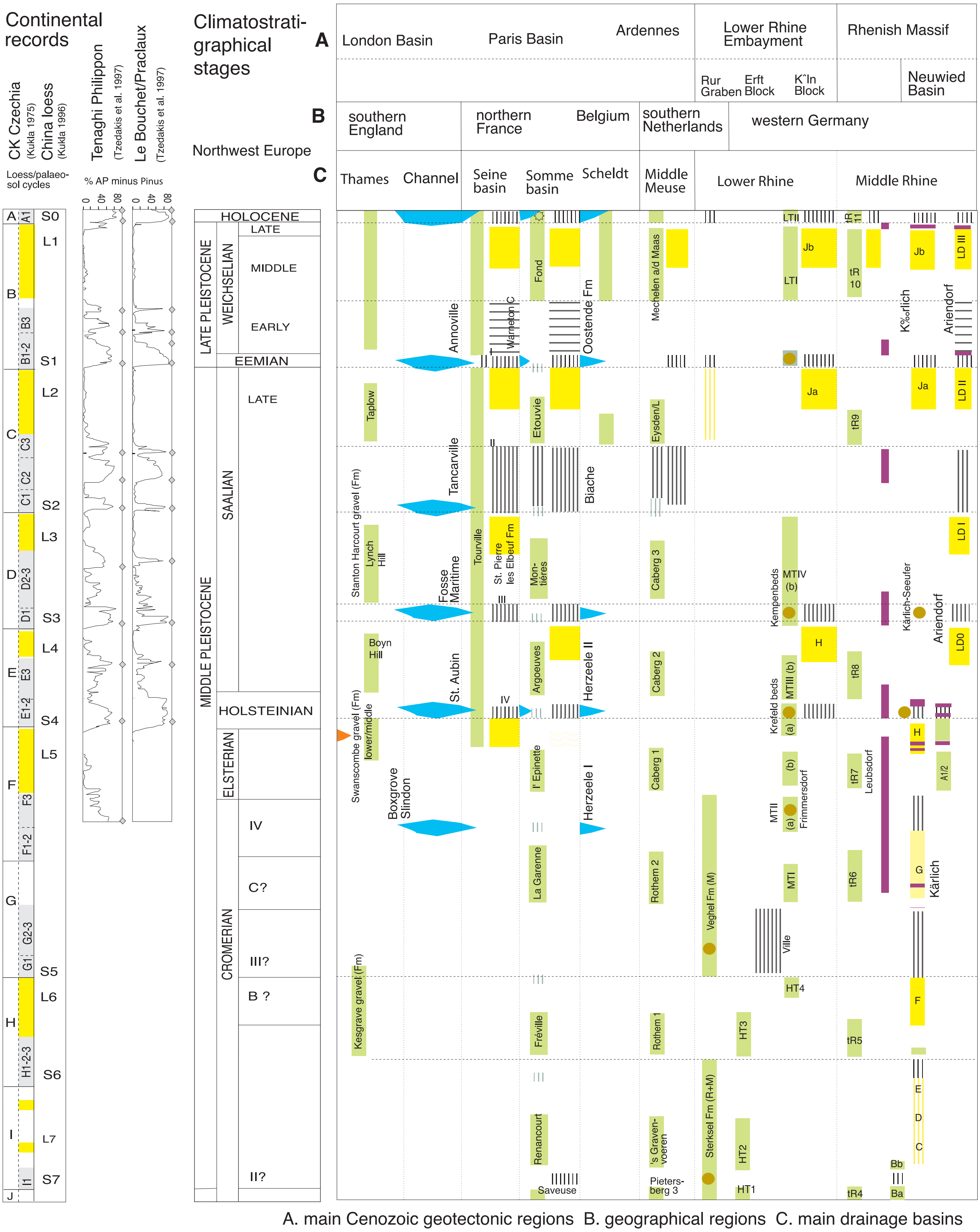
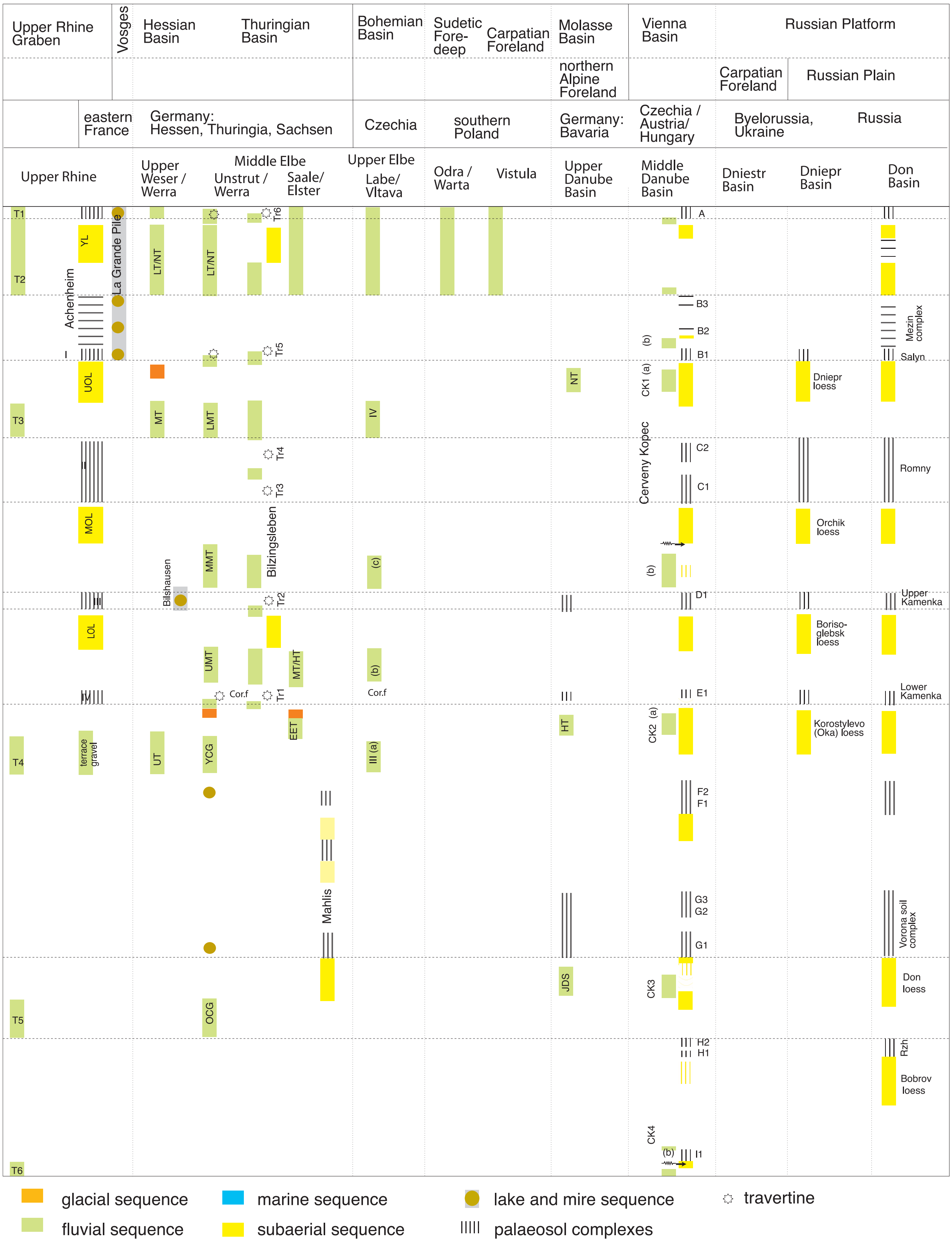


Figure 4.8 Middle and Late Pleistocene genetic sequence stratigraphy for the non-glaciated areas in Northwest and Central Europe.



Upper Rhine Graben
Vosges
Hessian Basin
Thuringian Basin
Bohemian Basin
Sudetic Fore-deep
Carpatian Foreland
Molasse Basin
Vienna Basin
Russian Platform
northern Alpine Foreland
Carpatian Foreland
Russian Plain
eastern France
Germany: Hessen, Thuringia, Sachsen
Czechia
southern Poland
Germany: Bavaria
Czechia / Austria/ Hungary
Byelorussia, Ukraine
Russia
Upper Rhine
Upper Weser / Werra
Middle Elbe
Unstrut / Werra
Saale/ Elster
Upper Elbe
Labe/ Vltava
Odra / Warta
Vistula
Upper Danube Basin
Middle Danube Basin
Dniestr Basin
Dniepr Basin
Don Basin
T1
T2
T3
T4
T5
T6
Achenheim
La Grande Pile
YL
UOL
MOL
LOL
terrace gravel
LT/NT
MT
LMT
MMT
UMT
YCG
OCG
UT
EET
MT/HT
Bilshausen
Bilzingsleben
Mahlis
Tr1
Tr2
Tr3
Tr4
Tr5
Tr6
Cor.f
IV
(c)
(b)
III (a)
NT
HT
JDS
Cerveny Kopec
CK1 (a)
(b)
CK2 (a)
CK3
CK4
A
B1
B2
B3
C1
C2
D1
E1
F1
F2
G1
G2
G3
H1
H2
I1
Dniepr loess
Orchik loess
Boriso-glebsk loess
Korostylevo (Oka) loess
Mezin complex
Salyn
Romny
Upper Kamenka
Lower Kamenka
Vorona soil complex
Don loess
Rzh
Bobrov loess
glacial sequence
fluvial sequence
marine sequence
subaerial sequence
lake and mire sequence
palaeosol complexes
travertine

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

4.4.1 Interpretation of the palaeoclimatic event markers

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

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

Events of global magnitude, which are responsible for wide-spread cyclicity in the sedimentary record, are associated with tectonics, palaeogeomagnetic reversals, climatic change and eustatic sea-level fluctuations. These events may serve as a global template for chronostratigraphical correlation, although operating at different scales. Geological and biological/ecological events identified in this thesis, as explained in *section 2.6.3*, not only refer to short-term catastrophic phenomena but particularly include climate-driven events, tectonics or sea-level changes with 5*th* and 4^{th} order frequencies of 0.001 - 0.1 Ma.
Glacial and periglacial aeolian (loess) sequences are markers with interregional event-stratigraphical significance, exclusively associated to mid-latitude glaciations and extreme cold deserts. The preserved sequences in most type regions, however, are represented by incomplete stratigraphical cycles. Cycle boundaries are spatially represented by wide-spread maximum distribution limits and temporally by basal unconformities in vertical geological sections. Nevertheless, the sequences can readily be related to events indicative for large-scale zonal and global climate change, such as glaciations, periglacial deserts and sea-level fluctuations for which ultimately the marine isotope stratigraphy can be used as a reference for timing and, to a lesser degree, patterning. They are summarised in *Figure 4.9* for Northwest and Central Europe on a relative time scale, together with bio- and chronological marker events.
The dynamic events have also drastically remodelled land surfaces, are responsible for major erosional unconformities and have created new depositional environments, for example, the lakes infilled during subsequent deglaciation. The number of preserved regional glacial and periglacial aeolian sedimentary cycles, initially determined by geographical position and ice-sheet dynamics/intensity, is eventually fixed by syn- and post-depositional features resulting from (repeated) erosion, burial, deformation and resedimentation.
The glacial and periglacial sequences left behind in renewed palaeogeographical situations have also preconditioned further palaeoenvironmental development in many type regions. The initially unvegetated post-glacial landscapes have subsequently been levelled by non-glacial environments or have otherwise been subjected to soil formation. These local and regional sequences and unconformities from fluvial, lacustrine, subaerial and other environments, coinciding and alternating with the wide-spread sequences, are embedded in the large-scale stratigraphical framework. Several of the small-scale sequences show detailed palaeoenvironmental and -climatic information, with a high time-resolution, which is of great importance in spatial analyses. Unfortunately, they also reflect bio-geographical and geotectonic variability which have not always been consistently assessed in large-scale correlation of climatically-induced sedimentary cycles in mid-latitude Europe.

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

In conclusion, the stratigraphical table in *Figure 4.9* shows a sequence of events for Northwest and Central Europe which is compatible with the sequence of palaeoenvironments revealed by:
- Lithostratigraphy, from both the glacial and extraglacial areas in Europe (and Eurasia),
- The limited amount of dating evidence available,
- The continuous pollen records of the French Maar lakes and Tenaghi Philippon as well as a number of fixed short-term pollen records from glacial lake sequences,
- Faunal evidence from local sequences, and,
- Independent evidence from major unconformities, such as fluvial terrace surfaces and soil complexes.

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

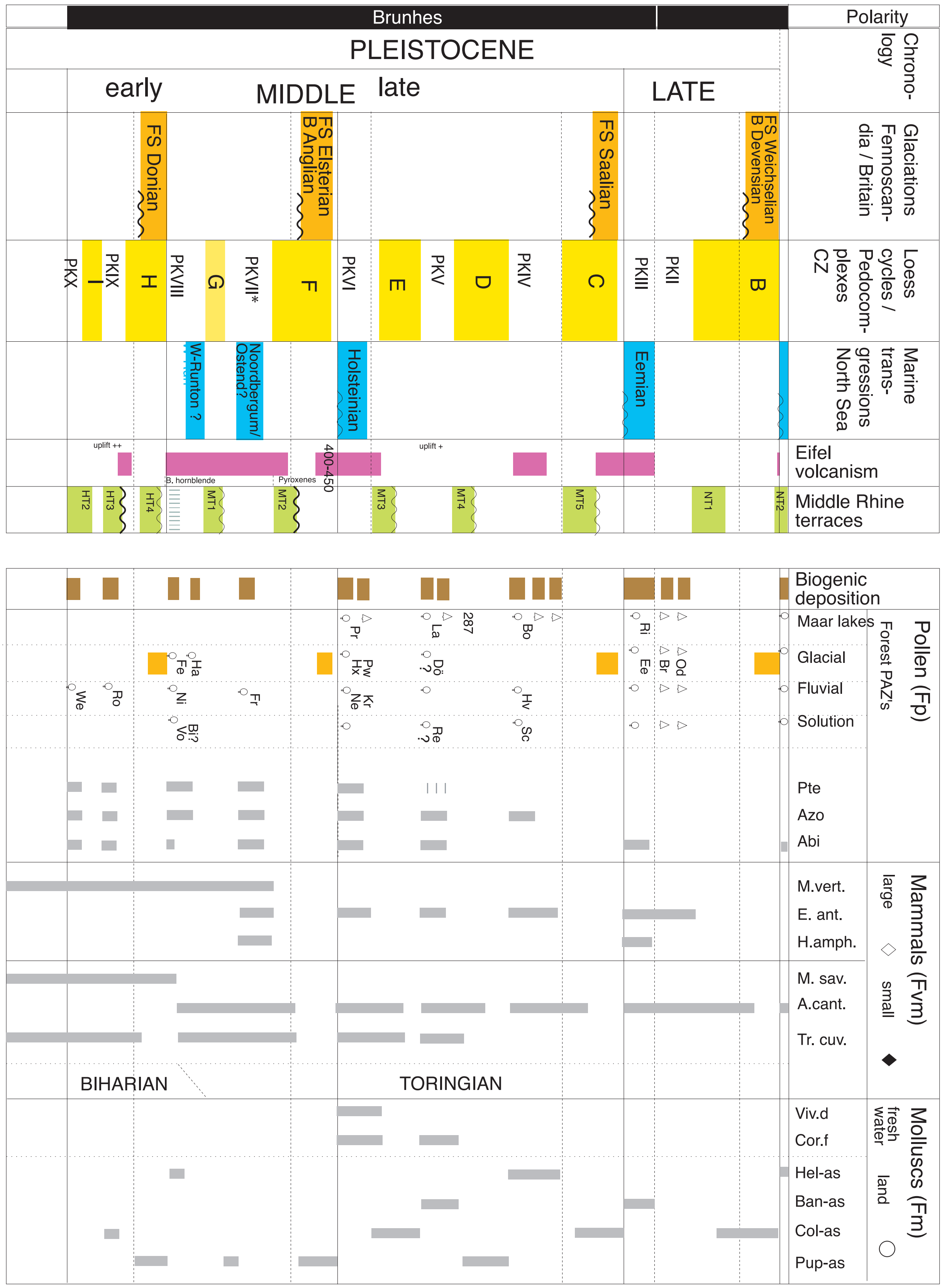


Figure 4.9 (Terrestrial) event stratigraphical subdivision and bio-indicators of the Middle and Late Pleistocene for Northwest and Central Europe.

4.4.2 Relevant chrono- and biostratigraphical markers of interregional significance

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

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

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

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

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

5 Regional geotectonic events (*next section*).

4.4.3 Regional geotectonic variability

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

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

Independent evidence of major neotectonic phases comes from both the glaciated lowland areas and the extraglacial terrace sequence stratigraphies in the tectonically active upland regions of Northwest and Central Europe. Here three major erosional steps separate the terrace sediment complexes north of the Alps within the Brunhes Chron. They comprise the Upper, Middle and Lower Terrace complexes, also dealt with in *section 4.3.2*. Kukla and Çilek (1996) associate them with regional tectonic re-arrangements or phases of uplift, relative to the basins, as a response to extreme glaciations. Although the latter two erosional anomalies may be related to glacio-isostatic effects of the Saalian and Elsterian glaciations, the erosional morpho-tectonic change in the early Middle Pleistocene, seems to be related to an independent tectonic event of accelerated uplift, dated roughly between 1.1 - 0.7 Ma. It separates the terrace accumulations of:
- The *Deckenschotter Complex* (Günzian/Haslachian/Mindelian Complex) from the *Hochterrassen* (Rissian/Würmian Complex) in the northern Alpine Foreland (nAF),
- The *CK4 terrace* from *CK3 terrace* in the loess terrace sequence of Červený Kopec in the eastern Alpine Foreland, and
- The *Hauptterrassen Complex* from the *Mittelterrassen Complex* in the Middle and Lower Rhine type areas.

Correlation is complicated because of regional differences. The dating of this tectonic erosional unconformity is based on:
- The presence of the Brunhes/Matuyama boundary in the nAF *Deckenschotter Complex* as well as in the Middle Rhine *Hauptterrassen Complex* which makes an early Middle Pleistocene

age plausible.

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

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

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

[2] *And partly still continuing.*

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

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

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

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

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

[8] *LAD: last appearance datum.*

[9] *FAD: first appearance datum.*