# A continent-wide framework for local and regional stratigraphies

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Chapter 2

# QUATERNARY TERRESTRIAL STRATIGRAPHY AND CORRELATION; A MULTIDISCIPLINARY APPROACH

## 2.1 Stratigraphical subdivision: some basic concepts and procedures

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

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

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

Stratigraphy starts in the field. Local-scale geological data from sections and cores and from different depositional environments are the basis for subdivision. Each classification system, by definition, is arbitrary and has its own hierarchy in which the upper category always includes the foregoing levels[2]. Basic stratigraphical procedures are lithostratigraphy, biostratigraphy and chronostratigraphy (*Figs. 2.1a* and *2.1c*). They serve best for marine and non-glacial sequences deposited in large-scale sedimentary basins spanning (tens of) millions of years, but are not quite satisfactory for the geologically short time span of the Quaternary with its highly varied terrestrial depositional record, the predominance of erosional surfaces and the absence of distinctive fossils. Available geomagnetic and geochronometric[3] dating methods are so far also inaccurate for the high resolution desired for the subdivision of this period.
Nonetheless, there are many kinds of Quaternary stratigraphical data that are useful in certain areas or for certain purposes. Data derived from a range of complementary techniques such as palaeomagnetic dating, geochronometric dating, geochemical analysis and seismic research can be of stratigraphical value and are frequently applied in smaller-scale subdivisions. Oxygen isotope stratigraphy applicable to ocean floor and ice cores has proved its effectiveness for global correlation of glaciation and deglaciation events and its potential to serve as a global time-based reference framework (*section 2.5.3* and *Chapter 6*).

### 2.1.1 Material descriptive units

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

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

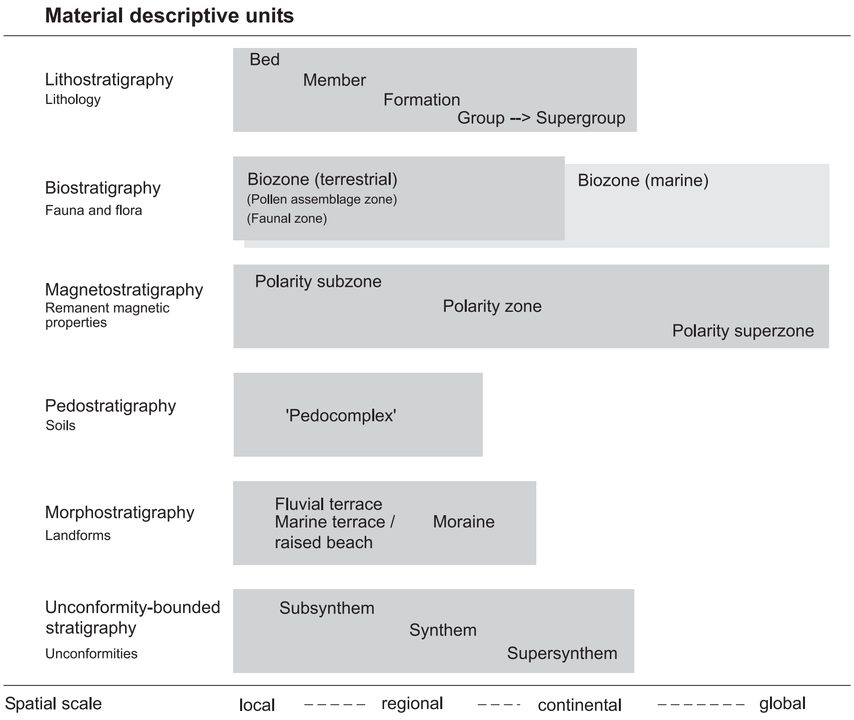
In the latest edition of the International Stratigraphic Guide (Salvador (*ed.*) 1994) two additional procedures are formally recognised which have become increasingly functional in terrestrial stratigraphy (*Fig. 2.1a*):

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

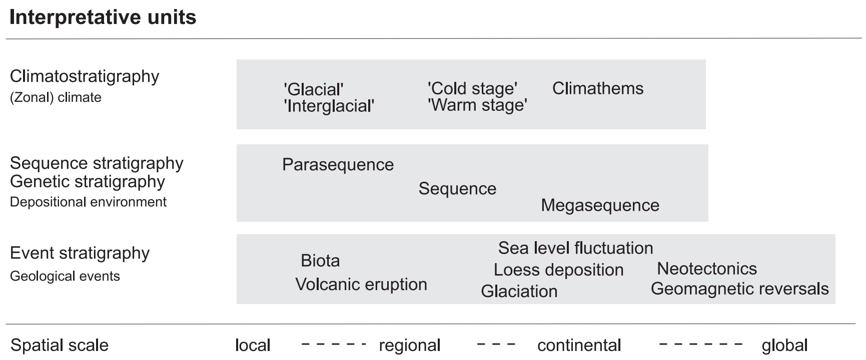
### 2.1.2 Interpretative units

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

Figure 2.1 Terrestrial stratigraphical classification and procedures:



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



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

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

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

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

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

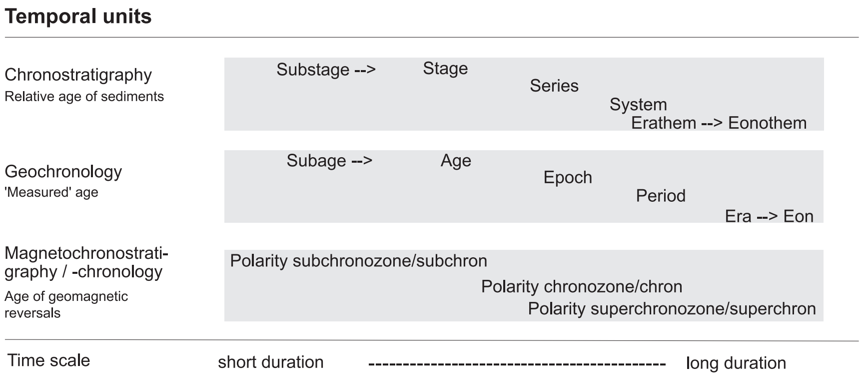
### 2.1.3 Temporal units

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

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

### 2.1.4 Correlation

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



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

## 2.2 The Quaternary System and Period

### 2.2.1 Terminology and historical background

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

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

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

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

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

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

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

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

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

### 2.2.2 Age and chronostratigraphical status

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

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

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

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

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

In conclusion, the status and conception of the Quaternary in the standard geological timescale remains a stratigraphical dilemma and an ongoing subject for debate. The geologically short time span of the Quaternary Period, together with the incompleteness of its system, particularly the terrestrial part, makes palaeontology of limited use as a primary criterion for chronostratigraphical subdivision. The high precision that is desired for the subdivision of the Quaternary simply cannot be achieved by traditional palaeontological zonation. Moreover, palaeomagnetism is of low resolution and (reliable) geochronometric dating methods, which reach beyond the radiocarbon dating limit of 40-50 k, are lacking.

On the other hand, when compared to earlier systems the deviant nature of the Quaternary record, dominated by cyclic zonal climatic change (well represented in the oceanic record), together with its different temporal scale and resolution are arguments to support the Quaternary as a discrete system rank unit. Despite some efforts which have been undertaken (Aubry *et al.* 1999) only the base of the Quaternary at Vrica is formally defined a GSSP until now. The International Subcommission on Quaternary Stratigraphy (ISQS) is in the process of defining GSSPs in the Quaternary system for the Early/Middle, Middle/Late Pleistocene and the base of the Holocene. For practical reasons the boundary levels of the marine isotope stratigraphy are commonly used as a reference and matched with regional stratotypes on the continents. This conception still meets criticism on the basis of traditional stratigraphical principles and methods (a.o. in Schoch 1989 and Gradstein *et al.* 2002). In every respect the status of the Pleistocene will remain Series/Epoch incorporated either within the Tertiary/Neogene System/Period or the Quaternary System/Period.

## 2.3 Nature of the Quaternary terrestrial succession

### 2.3.1 The incomplete terrestrial geological record

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

### 2.3.2 The interpreted terrestrial palaeoclimatic record

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

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

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

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

Praclaux in France (*Fig. 3.9*, de Beaulieu & Reille 1995, Tzedakis *et al*. 1997, de Beaulieu *et al*. 2001), and
- The Late Pleistocene pollen records from La Grande Pile and Les Echets in France (Woillard 1979; de Beaulieu & Reille 1987; Guiot *et al*. 1989, 1992).

Further important key stratigraphical sequences within Europe, although not continuous or superimposed, include:
- The combined loess/palaeosol and river terrace sections of Červený Kopec (in Slovakia, *Fig. 2.2*) and Krems (in Austria), spanning 9 glacial cycles within the Brunhes Chron (Kukla 1970, Fink & Kukla 1977),
- The Middle Pleistocene loess/palaeosol terrace sections with intercalated volcanic ash horizons of Kärlich and Ariendorf in the Middle Rhine valley in Germany, (a.o. Brunnacker *et al.* 1969, Schirmer (*ed.*) 1990, Boenigk 1995, Turner (*ed.*) 1997, Boenigk and Frechen 2001: *section 5.2*),
- The Somme valley terrace sequence in France (Antoine 1990 and 1994, Antione *et al.* 2003),
- The terrace sequence of the lower Thames valley (Gibbard 1985, Bridgland 1994, Schreve and Bridgland 2002),
- The Bilzingsleben terrace sequence in Thuringia/Germany (Mania 1993),
- The Schöningen sections in Lower Saxony/Germany (Thieme *et al.* 1993, Urban 1995) intermediate between the Elsterian and Saalian glacial sequences (*section 5.4*).

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

## 2.4 Scale and resolution of research

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

In addition to scale, the concept of resolution at which an object or a period of time is considered is of importance. In mapping, large and small scale refer to respectively high and low resolution images of areas. When related to temporal scales, resolution refers to the length of the temporal intervals that are considered, e.g. events reconstructed for short-term time periods are at high resolutions. Accordingly, scale involves the size and resolution of the described observations (minerals, beds, outcrops, formations), as well as the spatial and temporal resolution of the interpretation. Furthermore, the scale of interpretation incorporates resolutions dictated by the nature of the record (see previous section). Thus, the global implications of the fragmentary and largely undated continental Quaternary record therefore must be constrained to large-scale interpretations and low-resolution classification, at least beyond the radiocarbon dating limit of 40-50 ka. For the Middle Pleistocene this implies that in the best case the trends in the 100 ka climatic cyclicity of the marine isotope stratigraphy can be correlated. Only in some cases it will be possible to match short-term oscillations.

### 2.4.1 Spatial scale

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

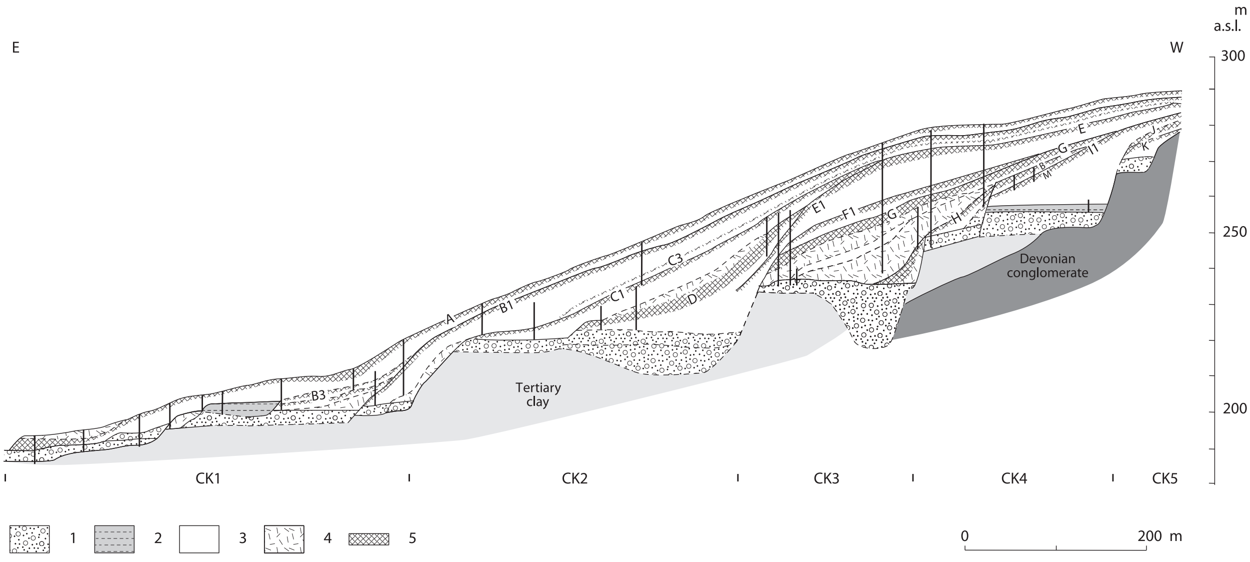


Figure 2.2 The terrace profile from Cervený Kopec along the Srvatka river and interpreted loess/palaeosol cycles (Kukla 1969, 1975). 1) fluvial terrace gravel; 2) fluvial silt; 3) loess; 4) slope deposits; 5) soil complex. For subdivision and environmental interpretation see Figure 3.2.

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

### 2.4.2 Temporal scale

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

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

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

## 2.5 Aims of subdivision: a global framework for regional stratigraphies

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

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

### 2.5.1 A supplementary large-scale stratigraphical framework for regional stratigraphies

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

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

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

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

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

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

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

### 2.5.2 Interpretation of climate type events

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

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

1. Proxy indicators of atmospheric condition (temperature and precipitation) such as:
   - Distribution and lithofacies characteristics of glacial and glacial-related sediments and associated landforms indicating ice-sheet expansion and ice-margin positions,
   - Distribution and lithofacies characteristics of periglacial loess deposits as indicators for cold, dry conditions and solifluction deposits indicating cold, humid conditions,
   - Distribution and lithofacies characteristics of fluvial sediments in recognising climatic regime during deposition,
   - Cryogenic structures in glacial, fluvial and aeolian periglacial environments indicating the nature and extent of permafrost,
   - Vegetational composition from pollen and plant macrofossil analysis in terrestrial (lacustrine, fluvial) and shallow marine sequences,
   - Microfaunal and macrofaunal assemblages in terrestrial (lacustrine, fluvial), shelf sea and raised marine environments,
   - Soil development and weathering characteristics within aeolian, fluvial and glacial sequences,
   - Growth frequency distributions of cave calcite deposits.
2. Evidence of relative sea-level as a reflection of global and local ice volume and lithosphere flexure inferred from the distribution of paralic and shallow marine deposits such as maximum flooding surfaces, transgressive surfaces, raised beaches and incised valleys.
3. Evidence of (geo)hydrological conditions from:
   - Deposits and landforms which reflect changing river courses and groundwater levels,
   - Groundwater chemistry reflecting the nature and rate of groundwater recharge,
   - Palaeo-lake levels which reflect changes in the surface water balance.

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

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

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

### 2.5.3 Relation of regional terrestrial events to the marine isotope stratigraphy

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

*[a] Matching of terrestrial and marine boundary levels*

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

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

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

*[b] Land-sea palaeoclimatic event correlation*

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

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

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

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

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

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

### 2.6.1 Unconformity-bounded stratigraphy: subdivision and terminology

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

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

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

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

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

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

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

### 2.6.2 (Genetic) sequence stratigraphy: subdivision and terminology

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

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

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

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

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

### 2.6.3 Event stratigraphy: subdivision and terminology

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

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

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

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

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

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

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

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

[4] *And holostratotype.*

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

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

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

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

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

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

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

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

[13] *See also section 6.3.1.*

[14] *Angular unconformities, disconformities.*

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

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

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

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

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