Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Global and Planetary Change 36 (2003) 201–208
GLOBAL AND PLANETARY CHANGE
www.elsevier.com/locate/gloplacha

Definition of the Middle–Upper Pleistocene boundary

P.L. Gibbard*

Godwin Institute of Quaternary Research, Department of Geography, University of Cambridge, Downing Street, Cambridge CB2 3EN, UK

Received 2 February 2000; accepted 23 February 2002

Abstract

The definition of a Middle–Upper Pleistocene Subseries boundary is discussed. This boundary is at present not formally defined, but has up till now been placed at the beginning of the Last Interglacial (Eemian, Mikulino, Sangamonian, etc.) or Marine Isotope Stage 5. Although it may seem attractive to define the boundary in an ocean sediment sequence, the inherent imprecision of most of such sequences, resulting from slow sedimentation rate, combined with the effects of bioturbation, suggests that for high-resolution stratigraphical purposes they are generally unsuitable for the definition of 'golden spike'-type, 'time–plane' boundaries. It is therefore proposed that the Saalian–Eemian stage boundary, and thus the Middle–Upper Pleistocene Subseries boundary-stratotype be defined from a terrestrial locality at −63.5 m below surface in the Amsterdam-Terminal borehole, The Netherlands. This parastratotype locality is also to be proposed as the Eemian Stage unit-stratotype.

Keywords: Pleistocene; Last Interglacial; Eemian

1. Introduction

The chronostratigraphy of the Pleistocene Series or its geochronological equivalent Epoch has been a topic of intensive discussion throughout the subject's history and remains so today. The extraordinary complexity of change during the time period and the widely held desire to recognize and correlate the changes across local areas, regions and indeed the world, whenever possible, seldom fails to cause heated discussion, whenever practitioners meet. With the recognition of the detail represented in the ocean sediment and, more recently, the ice-core sequences, emphasis has been focussed on attempts to identify and correlate ever smaller-scale events. This focus has held-aloft an important challenge to stratigraphers working in all environments, to address the implications of high- or even ultra-high resolution sequences. But in this 'hot-house' atmosphere of rapid advance, the stratigraphical nomenclature is becoming overstretched and somewhat impractical. Moreover, with this concentration on small-scale events, the validity and usefulness of larger-scale divisions of the Pleistocene have fallen from sight.

The need for precision in the subdivisions of the Pleistocene has long been recognized, particularly in Europe. After World War II, the previously acceptable reliance on Penck and Brückner's (1909–1911) Alpine scheme as a global standard became unsustainable; workers such as Van der Vlerk (1953)

* Tel.: +44-1223-333922; fax: +44-1223-333922.
E-mail address: plg1@cus.cam.ac.uk (P.L. Gibbard).

0921-8181/03/$ - see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0921-8181(02)00185-6

advocating the definition of longer, locally based, precisely defined stratigraphical schemes to classify and divide their sequences. By the early 1970s, stratigraphers saw a need to refine and formally define the larger-scale divisions of the Pleistocene driven by the increasing precision then being seen in the terrestrial and ocean sediment records. Thus in 1973, a Working Group, to examine the major divisions of the Pleistocene, was established at the INQUA Congress in New Zealand. Its primary objective was to establish boundaries for lower, middle and upper subseries of the Pleistocene Series (Epoch). It was also intended "to define these boundaries on the basis of criteria that would allow them to be as time-parallel as possible throughout the world in both marine and continental sediments" (Richmond, 1996). These objectives have yet to be fully achieved.

2. The term Pleistocene as a Series or Epoch

The term Pleistocene, originally defined by Lyell (1839), has become synonymous with the 'ice age'. Clearly therefore, it is virtually identical in meaning to the term Quaternary, defined by Desnoyers (1829), although of course the Pleistocene is defined as having ended 10 000 radiocarbon years ago and is followed by the Holocene Series in which we still live. Setting aside the obvious and frequently rehearsed philosophical debates that could be raised concerning the validity of separating the last 10 000 years from the previous 1.5 to 2.5 million years, it is clear that there are too many synonyms for this period. For example, the realization of this problem led West (1968) to suggest incorporating the post-glacial (Holocene) into the Pleistocene as a stage, termed the Flandrian. This has not found general acceptance, however, in spite of its attraction, although there is widespread acceptance that the last 10 000 years is simply an interglacial warm period exactly like those of the later Pleistocene (cf. Lowe and Walker, 1997, p. 1).

The difference between the term Quaternary and the terms Pleistocene and Holocene is, of course, one hierarchy, since in current use the former two are Series and the latter is a System. The term system, series and subseries and stage are chronostratigraphical units. The International Stratigraphic Guide (Hedberg, 1976, p. 72; Salvador, 1994) defines a chronostratigraphical unit as "a body of rock strata that is unified by being the rocks formed during a specific interval of geologic time". In other words, such a unit represents a body of rock strata. An accompanying geochronological unit represents the "intangible" geological time-equivalent of the "tangible" chronostratigraphical unit, i.e. it is a time interval during which a unit of rock strata accumulated. The hierarchy of the larger-scale chronostratigraphical (and geochronological) units in current use is as follows (cf. Hedberg, 1976; Salvador, 1994):

1. Cenozoic = Erathem (and Era).
2. Quaternary = System (and Period).
3. Pleistocene = Series (and Epoch).
4. Lower, Middle and Upper or Early, Middle and Late = subdivisions of series (and epochs)—i.e. subseries (or subepochs).

Therefore, the term Pleistocene is a series, a unit in the conventional chronostratigraphical hierarchy ranking intermediate between stage and system. A series is always a subdivision of a system; it is usually but not always divided into stages. Most systems have been divided into three series (Lower, Middle and Upper) (Hedberg, 1976, p. 72; Salvador, 1994) and each series commonly includes from two to six stages. The geochronological equivalent of the term series is epoch.

The constant confusion over the chronostratigraphical and geochronological terms has led to discussion over the last decade and the generally held opinion is that this duplication is unnecessary and confuses many (cf. Harland et al., 1989), although this has not found universal support. Nevertheless, the problem persists and in order to address it the Geological Society's Stratigraphical Commission (in Britain) have adopted Harland et al.'s (1989) suggestion by proposing that independent geochronology be dropped in favour of a united terminology for chronostratigraphy. Zalasiewicz et al. (in press) comment: "the deeply embedded, parallel chronostratigraphy/geochronology classifications are not merely a functionally outmoded, if harmless, relic of earlier geological thought. Rather, this entire duplicate panoply of hierarchical terminology is a hindrance to geological understanding. As regards the need to clearly separate rocks, processes and time, and as regards ease of grammatical usage, there seems to be no need to maintain two parallel nomenclatural hierarchies, despite them being deeply ingrained in the literature." They propose the adoption of the nomenclature of Harland et al. (1989) and have chronostratigraphy define a hierarchy of:

Eon
Era
Period
Epoch
(Subepoch)
Stage
Chronozone

According to Krumbein and Sloss (1963, p.46–47), "custom and usage have developed a tripartite subdivision of certain periods (Cambrian, Ordovician, Silurian, Triassic, Jurassic) or a simple two-way split. Epochs are readily identified by Early, Middle or Late, parallel series are specified by Lower, Middle or Upper attached to the system name. Generally, no ambiguity results if the time-stratigraphic value of them is clearly implied by the context of usage." Zalasiewicz et al. (in press) continue "The formal distinctions of 'lower', 'middle' and 'upper' (of chronostratigraphy) versus 'early', 'mid-' and 'late' (of geochronology) made sense when the 'stratigraphical column' (i.e. early versions of our current chronostratigraphical hierarchy) were either essentially lithostratigraphical or biostratigraphical in nature. Now that chronostratigraphy deals overtly with time, we suggest that both are not needed, and that that only 'early', 'mid-' or 'middle' and 'late' be retained formally (pace Harland et al., 1989) leaving 'upper', 'middle' or 'mid-' and 'lower' as useful informal terms.

The major divisions of the Pleistocene, Lower, Middle and Upper, are agreed to be subseries (or subepochs), according to Richmond (1996) and conform to the International Stratigraphic Guide recommendations (Hedberg, 1976, pp. 10, 68). Terms of this rank have been rarely used in the pre-Cenozoic, but the need to recognize small-scale time divisions in the Pleistocene, and indeed other Tertiary series sequences, justifies their usage. At present in the Pleistocene they remain undefined from stratotype localities in spite of the fact that in Europe at least these terms are used in a quasi-formal sense. The need to define such events at GSSPs has recently been re-emphasized by Aubry et al. (1999).

In order to improve this situation, the INQUA working group solicited opinion from a wide range and a large number of concerned workers (Richmond, 1996) to determine the appropriate way forward. The results proposed and approved at the XII INQUA Congress at Ottawa were summarized as follows:

> As evolutionary biostratigraphy is not able to provide boundaries that are as globally applicable and time-parallel as are possible by other means, the Lower–Middle Pleistocene boundary should be taken provisionally at the Matuyama–Brunhes palaeomagnetic reversal and the Middle–Upper Pleistocene boundary at the base of deep-sea Oxygen Isotope Stage 5. The lower, middle and upper units so delimited are recommended as informal subseries of the Pleistocene (Anonymous, 1988).

This 'semi-' formalization of subseries (and subepoch) boundaries in a sense recognized very much the prevailing usage of the terms Lower, Middle and Upper Pleistocene in northern Europe, where they were most used. Clearly, this subdivision led to the acceptance of units of greatly varied length and character. These variations reflect their development.

3. Development of the Subseries

The first usage of the terms Lower, Middle and Upper Pleistocene seems to have been at the 2nd INQUA Congress in Leningrad 1932 (Woldstedt, 1962), although they may have been used in a loose way before this time. The first application of these terms in a formal sense in English appears to have been by Zeuner (1935, 1959) and Hopwood (1935) and was based on characteristic assemblages of vertebrate fossils in the European sequence. They recognized three groupings which were progressively more modern in character, arguing that if the Pleistocene was 600 000 years long, as then thought, these three divisions would be of approximately equal duration. The time duration of the divisions was based on

Zeuner's application of the Milankovitch timescale to the geological record, as then understood, in particular from the Alpine glacial and the Mediterranean shoreline sequences. The earliest unit post-dated the so-called Villafranchian assemblage (Upper Pliocene), now thought to span the Upper Pliocene to earliest Pleistocene (Nilsson, 1983). Zeuner's (1935, 1959) proposed sequence was as follows.

Upper Pleistocene back to about 180 000 BP; Last Glaciation and Last Interglacial. *Elephas primigenius*, late *Elephas antiquus*, *Dama dama*, *Dicerorhinus merckii*, *Tichorhinus antiquitatis*, *Homo neanderthalensis*, *Homo sapiens*.

Middle Pleistocene about 180 000 to 425 000 BP; Penultimate Glaciation and Penultimate Interglacial. *Elephas trogontherii*, *E. antiquus*, *D. clactonianus*, *D. merckii*, *Homo* cf. *sapiens*.

Lower Pleistocene about 425 000 to 600 000 BP; Antepenultimate Glaciation, Antepenultimate Interglacial and Early Glaciation. *Elephas meridionalis*, *primitive*, *E. trogontherii* and *E. antiquus*, *Dicerorhinus etruscus*, *Dama savini*, *Machairodus*, *Homo* (*Pithecanthropus*) *erectus*, *H. heidelbergensis*.

Thus, as defined above, the Middle–Upper Pleistocene boundary would occur at the same position as that used at present in Europe, at the base of the Last Interglacial, i.e. the base of the Eemian Stage (Mikulino, Sangamonian). By 1962, the dating of this boundary had been revised by Woldstedt (1962, p. 10) to 120 000 years.

Since that time there has been little debate and discussion over the major subdivisions of the Pleistocene. One point that arises, however, is the great inequality of their durations which became apparent with the realization of the true length of the 'preglacial' Pleistocene in the 1960s–1970s. This, together with the inexorable desire to extend the base of the Pleistocene from the internationally agreed base at 1.8 to 2.6 My means that the Lower Pleistocene Subepoch (Subseries) varies in duration from 1 to 1.8 My. By contrast, the Middle Pleistocene lasted 670 ky and the Upper Pleistocene only 126–8 ky. This marked inequality led West (1968) to propose that the Upper–Middle Pleistocene boundary might be lowered to include the terrestrial Saalian (and equivalent stages) to increase the length of the former, but this has not found acceptance. The lack of debate over the issue of subepoch or subseries duration suggests that most workers are satisfied by their current usage and that there is no pressure for change. Perhaps, this is also a consequence that the subepoch or subseries terms are mostly restricted to use by terrestrial workers, marine colleagues apparently being content to divide ocean sequences into stages and series-level units. Yet, in the Pleistocene, the changes in the amplitude and timing of the isotopic oscillations could equally be used as a basis for of subepoch or subseries divisions. Ironically, they seem to occur at points close to those identified from the terrestrial record; major changes occurring close to the B/M magnetic reversal boundary at 775 ± 10 ka (Bassinot et al., 1994).

As noted above, the desire to make these units identifiable worldwide led the INQUA Commission on Stratigraphy working group, to place the Lower–Middle boundary at the Brunhes–Matuyama magnetic reversal epoch boundary; the 'Toronto Proposal' of Richmond (1996). Unfortunately, it is less easy to define the Middle–Upper boundary in the same fashion and therefore it seemed expedient to the working group to consider it equivalent to the base of Marine Isotope Stage (MIS) 5, following the long-established convention noted above. This proposal naturally follows from the acceptance that MIS 5 (Substage e) is the ocean equivalent of the terrestrial NW European Eemian Stage interglacial (Shackleton, 1977). The logic of placing the boundary in marine sediments follows the standard stratigraphical convention of positioning boundaries in continuous marine sequences whenever possible (Hedberg, 1976; Salvador, 1994).

4. Where precisely is the boundary?

Recent years have seen a marked growth in stratigraphy recognized from short-duration, often highly characteristic events. Attempts have been made, in turn, to use these events as a basis for correlation. This event stratigraphy, typically deposition of a tephra layer or magnetic reversals, can also include geological records of other potentially 'catastrophic', or more properly 'abrupt'-type events such as floods, tectonic movements, changes of sea level, widely recognized climate events and the like. Such events may be preserved in a variety of environmental settings and thus offer important potential tools for cross-correlation. Of particular importance for Pleistocene stratigraphy are the essentially time-parallel periods of rapid climate change termed 'terminations' (Broecker and van Donk, 1970), seen in ocean sediment oxygen isotope profiles. The major, dramatic changes in world ice-volume so indicated, imply climate shift from full glacial to interglacial conditions over short time spans of a few millennia. In favourable situations, these sharp changes can also be recognized on land as dramatic changes in pollen assemblage composition or other parameters, for example where sufficiently long and detailed sequences are available, such as in long lake cores (cf. Tzedakis et al., 1997). It may then, on face value, seem attractive to attempt to use such termination events as a potential means for land–sea correlation. However, their value for correlation may be limited in high sedimentation-rate sequences because the 'terminations' are not instantaneous, but have durations of several thousand years (Broecker and Henderson, 1998). These matters clearly concern questions of resolution and scale.

Termination II marks the major shift immediately before MIS 5, the change thought to represent the climatic event represented by the Saalian–Eemian (and equivalents) stage boundary in NW Europe. Martinson et al. (1987) calculated the date of the base of MIS 5 at ca. 130 000 BP, i.e. corresponding to the end of Termination II of the marine oxygen isotope sequences (Broecker and Van Donk, 1970). More recently, the mid-point of Termination II was recalculated to 128 000; the amelioration beginning at 132 000 and ending 6000 years later at 126 000, based on data from a series of high-resolution ocean core profiles (Broecker and Henderson, 1998). On this basis, the Last Interglacial duration would be 129–119 000, based on use of midpoints for defining MI stage or substage boundaries, according to Broecker and Henderson (1998). However, the direct land–sea correlations shown by Sanchez-Goñi et al. (1999) clearly indicate that a 'Younger Dryas-type' oscillation (? the Zeifen event) is included in the Termination II climate change. Moreover, ice-rafted debris is also found from this period in the cores immediately predating the end of the termination (Shackleton, personal communication). Thus, the Eemian interglacial (sensu stricto) must coincide only with the lightest isotopic values of Substage 5e beginning at 126 ka and the heavier isotope values towards the 5e/d boundary (the latter has not been precisely defined in the marine isotope records).

The precise recognition and timing of boundaries or events from the ocean sediment (MI) stages on land and vice versa is of great concern for the development of a fully integrated, high-resolution terrestrial–marine global stratigraphy. Until very recently, many had assumed or not seriously questioned whether the terrestrial and ocean stage boundaries were coeval. This was not perceived as a problem. It was generally assumed that boundaries identified using a variety of proxies on land were coeval with those seen in the ocean sediments. Yet we know that different proxies respond at different rates and in different ways to climate changes and these changes themselves may be time-transgressive. That these boundaries do not necessarily invariably occur at the same time has been unequivocally demonstrated by the work west of Portugal by Sanchez-Goñi et al. (1999). Here, the MIS 6/5e boundary has been shown to have been significantly earlier than the Saalian–Eemian stage boundary on land on the basis of pollen analysis of the marine sediments. The same point concerns the MIS 2/1 boundary which pre-dates the Holocene/Pleistocene Series (= Flandrian/Weichselian Stage) boundary by some 2–4000 years. It may well therefore be similar for other interglacials. Thus, if high-resolution terrestrial sequences and low-resolution marine sequences are to be correlated accurately, one clearly cannot assume that the boundaries recognized in these very different environmental situations are indeed coeval (cf. Gibbard and West, 2000).

The implications of this difference of timing of the MIS 5 basal boundary with that of the terrestrial Saalian–Eemian boundary implies that the placing of the Middle–Upper Pleistocene Subepoch or Subseries boundary at the base of MIS 5 no longer corresponds to its original usage. The question therefore is whether this situation is acceptable or not; a point of principle is at stake here. The answer clearly should be one of practicality and historical precedent, in the absence of compelling arguments for change which seem to be lacking. In view of the evidence now becoming available, regarding the difficulty of precisely positioning the subepoch or subseries boundaries in ocean sediment sequences, the simplest solution would seem to be to restore the Middle–Upper Pleistocene boundary to its original position, i.e. at the base of the terrestrial NW European Eemian Stage. The position of the boundary in ocean isotope sequences could thus be identified like that in the Iberian margin cores of Sanchez-Goñi et al. (1999) by correlation with the land; an approach consistent with that used to identify the Pleistocene–Holocene boundary in some situations.

This problem raises a further generally relevant point that an event stratigraphy, based on the equation of terminations in the marine isotope profiles with terrestrial sequence chronostratigraphical interglacial basal boundaries, is difficult to apply because of the 'lag' effect of 2000 years or more between the two sequences; this effect being further complicated where minor 'Younger Dryas-type' oscillations occur. Conversely, the more gradual decline in temperatures towards the ends of interglacial events suggests that the recognition of interglacial/glacial transitional boundaries, i.e. the bases of glacial (cold) stages, in both environments is likely to be less difficult notwithstanding the fact that the ends of interglacials in terrestrial sequences are very difficult to recognize precisely from fossil assemblages because of the apparent persistence of certain plant taxa into the subsequent stage, for example.

5. A 'golden spike' locality?

In keeping with the recommendations of Hedberg (1976), that boundary stratotype localities should be established for series- and system-status chronostratigraphical units, recently restated by Aubry et al. (1999), it is clearly vital that the major Pleistocene subdivisions are fixed in sediment reference profiles. The recent reinvestigations of the Amsterdam basin by the Netherlands' Geological Survey (NITG-TNO) for establishment of a new Eemian unit-stratotype, to supplement the original site at Amersfoort (Zagwijn, 1961, 1983), was partially undertaken with a view to identifying a locality at which the Middle–Upper Pleistocene Subepoch or Subseries boundary could also be recognized and defined.

In the new borehole at Amsterdam-Terminal in 1997 (Cleveringa, 1998), an attempt was made to provide a more complete sequence of the Eemian sequence and to undertake an exhaustive analysis of the sedimentological and palaeontolological evidence. The preliminary results from this parastratotype core (Bosch et al., 1998; Cleveringa, 1998; Burger, 1998; De Gans et al., 1998; Heergreen, 1998; van Leeuwen et al., 1998; Meijer and Pouwer, 1998; De Wolf, 1998) clearly indicate that an almost complete Eemian sequence is present here but that the Saalian–Eemian transition occurs in freshwater lake sediments at −63.5 m below surface, identified using palynological assemblages. Thus, the stage basal, boundary, and by implication the Middle–Upper Pleistocene Subepoch or Subseries boundary, occur in freshwater sediment here.

In view of the generally held opinion that important boundaries should be located in marine sediments, this boundary is not ideal. In spite of the difficulties, it might seem more appropriate that the equivalent Saalian–Eemian basal boundary, and thus the subepoch or subseries boundary, could be defined in the Iberian margin in marine core MD952042 (Sanchez-Goñi et al., 1999) where terrestrial–marine correlation is apparently unambiguously achieved. If this were accepted the boundary would occur at 25.60 m in this core. However, the inherent imprecision in most deep-sea sequences, resulting from slow sedimentation rate, combined with the effects of bioturbation (except in anoxic basins), and the problem of restricted accessibility, suggest that this site is not satisfactory for high-resolution stratigraphical purposes. Moreover, the isotope sequence from MD952042 in Sanchez-Goñi et al. (1999) is based solely on planktic foraminifera, rather than the normal combination of benthic and planktonic assemblages. This is because the former increase anomalously somewhat earlier than the latter; the reason for which is unclear but may involve the mutual timing of climate warming and continental ice retreat, the interpretation of which is currently under investigation (Shackleton, personal communication). Thus, the detailed interpretation of this core may be problematic. Taken together, this serves to reinforce the view that this site in particular, and commonly ocean sediments in general, is unsuitable for the positioning of 'golden spike'-type boundaries (Shackleton, personal communication). Thus, it seems expedient at present, to locate the Saalian–Eemian stage boundary, and by implication the Middle–Upper Pleistocene Subepoch or Subseries boundary 'golden-spike' stratotype in the Amsterdam-Terminal borehole. This parastratotype locality is also to be proposed as the Eemian Stage unit-stratotype by the Dutch colleagues (cf. Bosch et al., 1998; Cleveringa, 1998; Burger, 1998; De Gans et al., 1998; Heergreen, 1998; van Leeuwen et al., 1998; Meijer and Pouwer, 1998; De Wolf, 1998). Long-distance correlation can be thus be achieved using cross-correlation by bio-, isotope stratigraphy and so on.

In common with all stratigraphy, chronostratigraphical classification is a dynamic subject that should evolve as knowledge becomes available. Thus, the reference points proposed here should be seen as the most suitable at the time of writing. Nevertheless, it is recognized that should more appropriate localities be discovered, parastratotype reference points may be defined.

In addition, the positioning of these stratotype localities in Europe may be seen by those working beyond as simply propagating a Eurocentric vision. It must, however, be borne in mind that the Eemian Stage, together with the Pleistocene Subseries or Subepoch divisions, are historically northern European units. Clearly, the holostratotype for the type-Eemian must remain in Europe. Its base would then, possibly as an interim measure, define that of the Upper Pleistocene (maintaining the status quo), pending a wider search for a more suitable and globally correlatable section, in keeping with the view that subseries stratotypes have a global relevance and status not expected of stage stratotypes.

6. Conclusions

(1) In keeping with the recommendations of Hedberg (1976) and Salvador (1994), boundary stratotype localities should be established for series- and system-status chronostratigraphical units. Recently restated by Aubry et al. (1999), it is vital that the major Pleistocene subdivisions are fixed in sediment reference profiles.

(2) Following historical precedent in NW Europe, the Middle–Upper Pleistocene Subseries boundary corresponds with the Saalian–Eemian stage boundary. It is suggested that the former be positioned at the boundary stratotype of the latter at − 63.5 m below surface in the Amsterdam-Terminal borehole. This parastratotype locality will also to be proposed as the Eemian Stage unit-stratotype by Dutch colleagues in a separate publication.

(3) The precise recognition and timing of boundaries or events from the ocean sediment (MI) stages on land and vice versa is central to the development of a fully integrated, high-resolution terrestrial–marine global stratigraphy. However, the inherent imprecision in most deep-sea sediment sequences, resulting from slow sedimentation rate combined with the frequent impact of bioturbation (except in anoxic situations), suggests that for high-resolution stratigraphical purposes they are generally unsuitable for the positioning of 'golden spike'-type (GSSP) boundaries.

(4) The base of the Upper Pleistocene proposed here may be regarded as an interim measure, pending a wider search for a more suitable and globally correlatable section, in keeping with the view that subseries stratotypes have a global relevance and status not expected of stage stratotypes.

Acknowledgements

The author thanks Professor R.G. West, Professor Sir N.J. Shackleton, Dr. Th. Van Kolfschoten, Dr. J.A. Zalasiewicz and Dr. M.A. Head for helpful discussions and contributions to this paper.

References

Anonymous, 1988. Biostratigraphy rejected for Pleistocene subdivisions. Episodes 11, 228.

Aubry, M.-P., Berggen, W.A., van Couvering, J.A., Steininger, F., 1999. Problems in chronostratigraphy: stages, series, unit and boundary stratotypes, global stratotype section and point and tarnished golden spikes. Earth-Science Reviews 46, 99–148.

Bassinot, F.C., Labeyrie, L.D., Vincent, E., Quidelleur, X., Shackleton, N.J., Lancelot, Y., 1994. The astronomical theory of climate and the age of the Brunhes–Matuyama magnetic reversal. Earth and Planetary Science Letters 126, 91–108.

Bosch, J.H.A., Beets, Ch.J., Burger, A.W., Cleveringa, P., Herngreen, G.F.F., Klaver, G.T., Kruk, R.W., van Leeuwen, R.J.W., Meijer, T., Pouwer, R., de Wolf, H., 1998. The Eemian of the Netherlands; environment, climate and age. In: Gibbard, P.L., van Kolfschoten, Th. (Eds.), Volume of Abstracts: The Eemian; Local Sequences, Global Perspectives. SEQS Symposium, 6–11 September 1998 Kerkrade, The Netherlands, p. 9.

Broecker, W.S., Henderson, G.M., 1998. The sequence of events surrounding Termination II and their implications for the cause of glacial–interglacial CO_2 changes. Paleooceanography 13, 352–364.

Broecker, W.S., Van Donk, J., 1970. Insolation changes, ice volumes and the 18O record in deep-sea cores. Reviews of Geophysics and Space Physics 8, 169–198.

Burger, A.W., 1998. Borehole Amsterdam-Terminal: heavy-mineral data of the Eemian type area. In: Gibbard, P.L., van Kolfschoten, Th. (Eds.), Volume of Abstracts: The Eemian; Local Sequences, Global Perspectives. SEQS Symposium, 6–11 September 1998 Kerkrade, The Netherlands, p. 11.

Cleveringa, P., 1998. Borehole Amsterdam-Terminal: pollen analytical data of the Eemian type area. In: Gibbard, P.L., van Kolfschoten, Th. (Eds.), Volume of Abstracts: The Eemian; Local Sequences, Global Perspectives. SEQS Symposium, 6–11 September 1998 Kerkrade, The Netherlands, p. 15.

De Gans, W., Beets, D.J., Centineo, M.C., 1998. Distribution and sedimentology of Eemian deposits in the western Netherlands with special reference to the Amsterdam glacial basin. In: Gibbard, P.L., van Kolfschoten, Th. (Eds.), Volume of Abstracts: The Eemian; Local Sequences, Global Perspectives. SEQS Symposium, 6–11 September 1998 Kerkrade, The Netherlands, p. 26.

De Wolf, H., 1998. Borehole Amsterdam-Terminal: diatom flora of the Eemian type area. In: Gibbard, P.L., van Kolfschoten, Th. (Eds.), Volume of Abstracts: The Eemian; Local Sequences, Global Perspectives. SEQS Symposium, 6–11 September 1998 Kerkrade, The Netherlands, p. 90.

Desnoyers, J., 1829. Observations sur un ensemble de dépôts marines. Annales des Sciences naturelles (Paris), 171–214, 402–491.

Gibbard, P.L., West, R.G., 2000. Quaternary chronostratigraphy: the nomenclature of terrestrial sequences. Boreas, 29, 329–336.

Harland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G., Smith, D.G., 1989. A Geologic Time Scale. Cambridge Univ. Press, Cambridge, 263 pp.

Hedberg, H.D., 1976. International Stratigraphic Guide. Wiley-Interscience, New York. 200 pp.

Heergreen, G.F.F., 1998. Borehole Amsterdam-Terminal: dinoflagellates of the Eemian type area. In: Gibbard, P.L., van Kolfschoten, Th. (Eds.), Volume of Abstracts: The Eemian; Local Sequences, Global Perspectives. SEQS Symposium, 6–11 September 1998 Kerkrade, The Netherlands, p. 33.

Hopwood, A.T., 1935. Fossil elephants and Man. Proceedings of the Geologist's Association 46, 46–60.

Krumbein, W.C., Sloss, L.L., 1963. Stratigraphy and Sedimentation, 2nd ed. Freeman, San Francisco.

Lowe, J.J., Walker, M.J.C., 1997. Reconstructing Quaternary Environments, 2nd ed. Longman, London, 446 pp.

Lyell, C., 1839. Nouveaux éléments de Géologie. Pitois-Levrault, Paris, 648 pp.

Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore, T.C., Shackleton, N.J., 1987. Age dating and the orbital theory of the ice ages: development of a high-resolution 0 to 300 000 year chronostratigraphy. Quaternary Research 27, 1–29.

Meijer, T., Pouwer, R., 1998. Borehole Amsterdam-Terminal: molluscan analysis of the Eemian type area. In: Gibbard, P.L., van Kolfschoten, Th. (Eds.), Volume of Abstracts: The Eemian; Local Sequences, Global Perspectives. SEQS Symposium, 6–11 September 1998 Kerkrade, The Netherlands, p. 51.

Nilsson, T., 1983. The Pleistocene. Reidel, Dordrecht, p. 651.

Penck, A., Brückner, E., 1909–1911. Die Alpen im Eiszeitalter. 1–3. Tauchuitz, Leipzig, 1199 pp.

Richmond, G.M., 1996. The INQUA-approved provisional Lower–Middle Pleistocene boundary. In: Turner, C. (Ed.), The Early Middle Pleistocene in Europe. Balkema, Rotterdam, pp. 319–326.

Salvador, A.S., 1994. International Stratigraphic Guide, 2nd ed. Geological Society of America, Boulder. 214 pp.

Sanchez-Goñi, M.F., Eynaud, F., Turon, J.L., Shackleton, N.J., 1999. High resolution palynological correlation off the Iberian margin: direct land–sea correlation for the Last interglacial complex. Earth and Planetary Science Letters 171, 123–137.

Shackleton, N.J., 1977. The oxygen isotope stratigraphic record of the Late Pleistocene. Philosophical Transactions of the Royal Society of London, B 280, 169–182.

Tzedakis, P.C., Andrieu, V., Beaulieu, J.L., Crowhurst, S., FollierI, M., Hooghiemstra, H., Magri, D., Reille, M., SadorI, L., Shackleton, N.J., Wijmstra, T.A., 1997. Comparison of terrestrial and marine records of changing climate of the last 500 000 years. Earth and Planetary Science Letters 150, 171–176.

Van der Vlerk, I.M., 1953. The importance of the use of local subdivisions of the Pleistocene. Actes du IV Congrès International du Quaternaire. Roma-Pisa, Août-Septembre. Instituto Italiano di Paleontologia Umana, Roma.

van Leeuwen, R.J.W., Beets, Ch.J., Beets, D.J., Bosch, J.H.A., Burger, A.W., Cleveringa, P., Herngreen, G.F.F., Klaver, G.T., Kruk, R.W., Langereis, C.G., Meijer, T., Pouwer, R., de Wolf, H., 1998. Borehole Amsterdam-Terminal. In: Gibbard, P.L., van Kolfschoten, Th. (Eds.), Volume of Abstracts: The Eemian; Local Sequences, Global Perspectives. SEQS Symposium, 6–11 September 1998 Kerkrade, The Netherlands, p. 46.

West, R.G., 1968. Pleistocene Geology and Biology. Longman, London.

Woldstedt, P., 1962. Über die Benennung einiger Unterabtielungen des Pleistozäns. Eiszeitalter und Gegenwart 3, 14–18.

Zagwijn, W.H., 1961. Vegetation, climate and radiocarbon datings in the late Pleistocene of the Netherlands: I. Eemian and Early Weichselian. Mededelingen van de Geologische Stichting. Nieuwe Serie 14, 15–45.

Zagwijn, W.H., 1983. Sea-level changes in the Netherlands during the Eemian. Geologie en Mijnbouw 62, 437–450.

Zalasiewicz, J.A., Allen, P.M., Bevins, R.E. Brenchley, P.B., Cope, J.C.W., Evans, J.A., Gale, A.S., Gawthorpe, R.L., Gibbard, P.L., Gregory, F.J., Hesselbo, S.P., Marshall, J.E.A., Knox, R.W.O., Oates, M.J., Rawson, P.F., Riley, N.J., Rushton, A.W.A., Smith, A.G., Trewin, N.H., in press. Simplifying stratigraphical time. Journal of the Geological Society.

Zeuner, F.E., 1935. The Pleistocene chronology of central Europe. Geological Magazine 72, 350–376.

Zeuner, F.E., 1959. The Pleistocene Period. Hutchinson, London, p. 447.