PERGAMON

Quaternary Science Reviews 18 (1999) 1143–1150

QSR VIEWPOINT

Viewpoint

# Isotopic 'events' in the GRIP ice core: a stratotype for the Late Pleistocene

M.J.C. Walker[a,*], S. Björck[b], J.J. Lowe[c], L.C. Cwynar[d], S. Johnsen[e], K.-L. Knudsen[f], B. Wohlfarth[g], INTIMATE group[1]

[a]Department of Geography, University of Wales, Lampeter, Ceredigion SA48 7ED, Wales, UK
[b]Geological Institute, University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen, Denmark
[c]Department of Geography, Royal Holloway, University of London, Egham, Surrey TW20 0EX, UK
[d]Department of Biology, University of New Brunswick, Fredericton, New Brunswick, Canada E3B 6E1
[e]Niels Bohr Institute of Astronomy, Department of Geophysics, University of Copenhagen, Copenhagen, Denmark
[f]Department of Earth Sciences, University of Aarhus, DK-8000 Aarhus C Denmark
[g]Department of Quaternary Geology, Lund University, Tornavägen 13, S-223-62, Lund, Sweden

**Abstract**

An event stratigraphy for the Last Termination, based on the stratotype of the GRIP ice-core record, has been outlined for the North Atlantic region. It is suggested that such an approach to stratigraphic subdivision may offer a more satisfactory alternative to conventional stratigraphical procedures for those parts of the recent Quaternary record that are characterised by rapid and/or short-term climatic fluctuations. 

## 1. Introduction

It has frequently been argued that the subdivision of, and correlation between, Quaternary sequences should follow conventional geological procedures (e.g. Bowen, 1978). Using this approach, the Quaternary record should be classified initially on the basis of observable lithostratigraphic and/or biostratigraphic characteristics and employing, wherever possible, regional type sequences as reference standards or stratotypes (Rose, 1989; West, 1989). Once a series of litho- or biostratigraphic units has been defined, sequences of strata can be divided into chronostratigraphic units that correspond to intervals of time, based on independent methods of dating, and these then form the basis for inter-site correlation (Hedberg, 1970).

In practice, however, the fragmented nature of the terrestrial (and also of some marine) stratigraphic records, the considerable spatial variation in type and thickness of sediments, the limited lateral continuation of many deposits, the spatial and temporal contrasts in Quaternary environments as reflected in the biostratigraphic record and, in particular, the apparently time-transgressive nature of Quaternary stratigraphic boundaries, all mean that conventional geological procedures are difficult to apply to many Quaternary sequences (Lowe & Walker, 1997). The problem is most apparent during the transition from the Last Cold Stage to the present Interglacial (the 'Last Termination' cf. Broecker, 1984), when climatic shifts of considerable magnitude occurred over timescales that are measurable in centuries or less (e.g. Alley *et al.*, 1993; Taylor *et al.*, 1993; Hughen *et al.*, 1996). In subdividing, classifying and correlating between the deposits that have accumulated during the course of this time interval, Quaternary scientists have, in the main, attempted to follow conventional geological practices, despite the fact that these approaches were never designed for such fine-scale resolution of the stratigraphic record. This has led to problems in the designation and interpretation of stratigraphic units from, and in the development of an appropriate stratigraphic nomenclature for, this episode of rapid climatic change.

* Corresponding author. Tel.: + 44-1570-424736.
*E-mail address:* walker@lamp.ac.uk (M.J.C. Walker)

[1] INTIMATE: INtegration of Ice-core, MArine and TErrestrial records, is a core programme of the INQUA (International Quaternary Union) Palaeoclimate Commission. The aim is to synthesise data from the marine, terrestrial and ice-core realms for the North Atlantic region during the course of the Last Termination

0277-3791/99/$ - see front matter 
PII: S0277-3791(99)00023-2

The INTIMATE group has recently described a new approach to the subdivision of the Last Termination, employing an event stratigraphy based on the oxygen isotope signal in the GRIP Greenland ice core (Björck et al., 1998). Here we respond to an invitation from the Editor of *Quaternary Science Reviews* to explain further the rationale that lay behind this proposal, and take the opportunity to discuss some of the wider implications. We suggest that the notion of an 'event stratigraphy' may have applications to other parts of the recent geological record which are characterised by rapid climatic changes.

## 2. The Last Termination in the Quaternary record

### *2.1. Lithostratigraphic and biostratigraphic subdivision*

The sequence of events during the transition from the Last Cold Stage to the present Interglacial (the Last Termination or the 'Lateglacial period', which spans the time interval approximately from 15.0 to 10.0 k $^{14}$C yr BP, or c. 18.0–11.5 k cal yr BP) was first established on the basis of lithological and palaeobotanical evidence from limnic sequences in NW Europe. In many lake sediment records, diamicts or other largely unfossiliferous deposits from the Last Cold Stage are overlain by organic sediment, reflecting ameliorating climatic conditions. This, in turn, is succeeded by a lithological unit with reduced organic content indicative of a return to periglacial conditions. The initial episode of organic sediment accumulation has been referred to as the 'Bølling-Allerød' interval (after sites in Denmark), while the subsequent short-lived colder phase was termed the 'Younger Dryas' (based on the presence of leaves of *Dryas octopetala* in the sediments), an 'Older Dryas' cold episode having previously been identified in some areas between the 'Bølling' and 'Allerød' warm phases on the basis of cold-climate sediments or vegetational evidence (Andersson, 1896; Hartz & Milthers, 1901). This nomenclature was later absorbed into the NW European pollen stratigraphic scheme of Jessen (1935,1938), so that pollen zone III was equated with the 'Younger Dryas', zone II with the 'Allerød', and zones Ia, Ib and Ic with the 'Oldest Dryas', 'Bølling' and 'Older Dryas' respectively. Hence, what was initially a conventional *lithostratigraphic* and/or *biostratigraphic* subdivision of the Lateglacial sediment record in particular parts of NW Europe, became transformed into a *climatostratigraphic* subdivision that was considered to have relevance at the continental scale. Moreover, as the pollen zones were considered to be broadly time-synchronous the biostratigraphic boundaries were assumed to provide a basis for *chronostratigraphy*, and the nomenclature became generally accepted as denoting a series of *time-stratigraphic units*.

### *2.2. Chronostratigraphic subdivision*

A time-stratigraphic framework for the NW European Lateglacial was first set out by Mangerud, Andersen, Berglund and Donner (1974), who incorporated the above nomenclature into a sequence of chronozones based on radiocarbon dates. Under their scheme, the 'Bølling Chronozone' (including the 'Oldest Dryas' episode) was defined as the time interval from 13.0 to 12.0 k $^{14}$C yr BP, the 'Older Dryas Chronozone' from 12.0 to 11.8 k $^{14}$C yr BP, the 'Allerød Chronozone' from 11.8 to 11.0 k $^{14}$C yr BP, and the 'Younger Dryas Chronozone' from 11.0 to 10.0 k $^{14}$C yr BP. The nomenclature that had originally been introduced to designate biostratigraphic (and climatostratigraphic) zones was therefore now employed in a strictly chronostratigraphic sense. This chronostratigraphy has subsequently been widely adopted and the terminology has been applied to records based on a variety of climatic proxies from the terrestrial, ice-core and marine realms.

### *2.3. Problems with the application of conventional stratigraphic procedures*

Although the chronostratigraphic approach follows (in the main) conventional geological procedures (e.g. Hedberg, 1970; North American Commission on Stratigraphic Nomenclature, 1983; Whittaker *et al*., 1991; Salvador, 1994), and despite the fact that it has been enthusiastically adopted by many Quaternary scientists, it is our view that it is not, in practice, a completely satisfactory approach either to stratigraphic classification or to correlation. The arguments are set out at length in Björck *et al.* (1998), but are rehearsed here briefly, as they may have implications for the stratigraphic subdivision of other parts of the recent geological record that are characterised by frequent, and often abrupt, climatic fluctuations.

Questions about the validity of a chronostratigraphic subdivision of the Lateglacial record revolve around three principal issues: terminology, time-transgression and dating. The first applies, in particular, to the Lateglacial period, but the last two have much wider ramifications. We deal first with terminological matters. In their 1974 paper, Mangerud et al. employed a nomenclature that had first been introduced to describe palaeobotanically-defined climatic episodes, but which had then been equated with pollen zones that were assumed to be time-synchronous. Because of the long history of their use, however, the terms 'Bølling', 'Allerød', 'Older' and 'Younger Dryas' have associations and connotations, sometimes with local variations in meaning, and hence in the literature these terms have been used at various times as pollen-defined biozones, geologic-climatic (climatostratigraphic) units or chronozones. Matters are further complicated by the fact that there is no internationally acknowledged type-section for the Lateglacial. Although the terms 'Bølling' and 'Allerød' derive from localities in Denmark where deposits relating to these warmer intervals were first described, the original sites are not regarded as appropriate reference sections. Indeed, nowhere in Europe is there a designated stratotype for the Last Termination.

The problems of terminological imprecision, historical association and the lack of an appropriate reference site are compounded by the fact that in the Mangerud et al. chronostratigraphic classification, the original bases for the chronozones were radiocarbon-dated *biozones*. Chronozones, by virtue of their definition, have boundaries that are time-parallel, whereas biozone boundaries, which reflect biological response to climatic/environmental changes that are spatially and temporally diachronous, are inherently time-transgressive. In the pre-Quaternary geological record, where temporal resolution is lower, biozone boundaries may *appear* to be time parallel. In the Lateglacial, however, where the stratigraphic record is much more precisely-defined, time-transgression is readily detectable (see e.g. Coope, Lendahl *et al*., 1998; Witte *et al*., 1998) and hence biozone and chronozone boundaries will seldom (and, indeed, should not) coincide. A further difficulty with the Mangerud et al. chronostratigraphy is that it is based solely on radiocarbon dating. Despite the fact that this is the most widely used technique for dating Late Quaternary events, problems arising from temporal variations in atmospheric $^{14}$C concentration mean that key chronozone boundaries, in particular the beginning and end of the Younger Dryas, are difficult to date precisely, because they occur within 'radiocarbon plateaux' of near-constant $^{14}$C age (Ammann & Lotter, 1989; Björck *et al*., 1996; Kitagawa & van der Plicht, 1998). This, allied with other potential error sources, such as reservoir effects in both limnic and marine sequences, along with a range of site-, sample- or laboratory-specific factors (Lowe, 1991), means that the radiocarbon timescale can no longer be regared as providing a satisfactory basis for a Lateglacial chronostratigraphy.

It would appear, therefore, that the subdivision, classification and correlation of the Last Termination cannot be satisfactorily achieved using conventional litho- and/or biostratigraphic approaches, partly because of the highly fragmented nature or inadequate temporal resolution of the stratigraphic record, but principally because of the problems of time-transgression. Moreover, despite its widespread application, radiocarbon dating cannot provide a satisfactory basis for a chronostratigraphy. An alternative approach is therefore required, and the INTIMATE group has proposed that the classification and subdivision of the Last Termination in the North Atlantic record be related to an 'event stratigraphy' based on the Greenland ice-core record.

## 3. The concept of an event stratigraphy

According to Whittaker *et al.* (1991), 'events' are short-lived occurrences that have left some trace in the geological record, and which can therefore be used as a basis for correlation. Events include, *inter alia*, volcanic eruptions, earthquakes, glacier margin oscillations, floods, storms, mass movements, climatic events and sea-level changes. These events are interpreted from evidence in the rock/sediment record, and hence correlation between sequences is essentially inferential as it is determined by stratigraphic patterns in a wider geological context, as opposed to being based on distinctive characteristics or properties of the rock/sediments themselves. In this respect, climatostratigraphy, which involves the designation of 'geologic-climatic units', and which is widely employed in Quaternary science (Lowe & Walker, 1997), is a type of event stratigraphy. Whittaker *et al.* (1991) observed that 'perhaps the best prospects for high-resolution event stratigraphy come from geochemical techniques, for instance by the use of stable isotopes, such as oxygen....' (p. 820). They also noted the way in which a relatively complete climatic record based on $^{18}$O/$^{16}$O ratios in microfossils in deep ocean cores had become the accepted standard against which fragmentary continental sequences can now be compared (e.g. Shackleton & Opdyke, 1973; Shackleton *et al*., 1990).

## 4. An event stratigraphy based on the GRIP Greenland ice core record

Although the deep-ocean isotopic record undoubtedly constitutes an unparallelled template for the classification and correlation of the Quaternary at the global scale, it is generally insufficiently precise or finely resolved to register the abrupt climatic changes of the Late Quaternary. In the Greenland ice sheet, however, a comparable oxygen isotope signal is preserved which provides a continuous, sensitive and high-resolution record of climatic changes, not only in the vicinity of the Greenland ice sheet, but in other areas of the Northern Hemisphere as well (Hughen *et al*., 1996; Taylor *et al*., 1997). As such, it constitutes a unique reference section for the entire North Atlantic region throughout the course of the Last Termination. The most detailed isotopic profile is that from the GRIP ice core (Johnsen *et al*., 1992,1997; Dansgaard *et al*., 1993), and the INTIMATE group has recommended that the GRIP core should become the type profile for this time period (Björck *et al*., 1998).

Adopting the 'count from the top' procedure that has proved to be so successful in the development of the marine oxygen isotope record, the GRIP record has been divided into a sequence of 'isotopic events' which can be dated in GRIP ice-core years. The timescale is based on

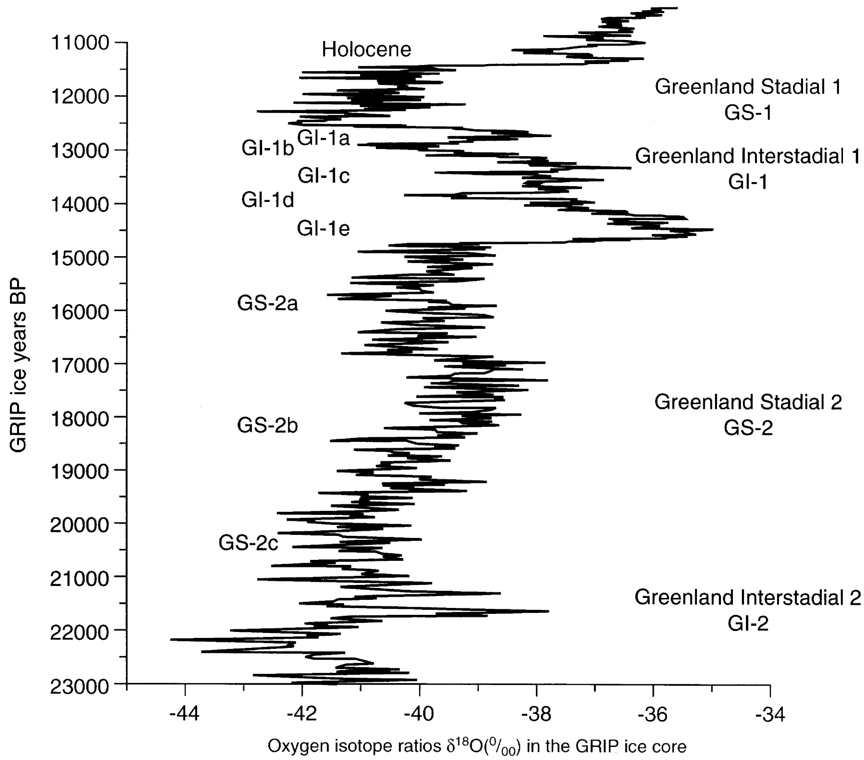


Fig. 1. The $\delta^{18}O$ record (SMOW) from the GRIP ice core (Johnsen *et al.*, 1992; Dansgaard *et al.*, 1993) between 11.0 and 23.0 k GRIP yrs BP showing the division of the oxygen isotope profile into interstadial (and sub-interstadial) and stadial (and sub-stadial) events (after Björck *et al.*, 1998)

the counting of annual ice layers down from the surface to 14.5 k GRIP yrs BP, and below that by the use of a steady-state ice-flow model (Dansgaard *et al.*, 1993; Johnsen *et al.*, 1997). The 'events' comprise clearly-defined, high-amplitude cold (stadial) and warmer (interstadial) episodes, the former designated by the prefix 'GS' (Greenland Stadial) while the latter have the prefix 'GI' (Greenland Interstadial). In addition, it is possible to recognise events of lower amplitude and shorter duration (sub-stadials and sub-interstadials): hence GI-1 can be divided into three warmer sub-interstadials (GI-1e, GI-1c and GI-1a) and two sub-stadials (GI-1d and GI-1b). Similarly, GS-2 is divisible into two colder episodes (GS-2c and GS-2a) separated by a warmer interval (GS-2b). Details of these are shown in relation to the oxygen isotope trace in Fig. 1 and in relation to ice-core years in Table 1.

The advantages of this approach to the subdivision of the Last Termination are several. It is based on a single climatic proxy (the oxygen isotope signal) from what can be regarded as a type sequence, and forms a continuous record throughout the designated time interval. It follows the established and successful stratigraphic practice in deep-ocean isotopic stratigraphy of numbering down-core alternating warm and cold episodes. Like the ocean record, it embodies sufficient flexibility to denote stages and sub-stages, the isotopic profile at the type site is underpinned by an independent chronology (in ice core years), and the scheme appears to be applicable throughout the North Atlantic province. Moreover, it finds parallels in both terrestrial and marine stratigraphic records.

Table 1
Chronology for isotopically-defined events and episodes between 11.0 and 23 k GRIP yrs BP in the GRIP ice core (after Björck *et al.*, 1998). The timescale is an unpublished revision of that described in Johnsen *et al.* (1997) and has been obtained by counting annual ice layers to 14.5 k GRIP yrs BP; below that it is based on ice-flow modelling. Ages are rounded to 50 yrs. Note that this differs from the stratigraphically-based timescale of Hammer *et al.* (1997). Further amendments to the GRIP chronology are anticipated, however, and the timescale shown here must still be regarded as preliminary.

| Events | Episodes | Ice-core depth (m) for the onset | Ice-core age k GRIP yr BP for the onset |
|---|---|---|---|
| Holocene epoch | | 1623.6 | 11,500 |
| GS-1 | | 1661.5 | 12,650 |
| | GI-1a | 1671.7 | 12,900 |
| | GI-1b | 1680.5 | 13.150 |
| | GI1c | 1713.7 | 13,900 |
| | GI-1d | 1719.2 | 14,050 |
| GI-1 | GI-1e | 1753.4 | 14,700 |
| | GS-2a | 1823.7 | 16,900 |
| | GS-2b | 1901.3 | 19,500 |
| GS-2 | GS-2c | 1939.1 | 21,200 |
| GI-2 | | 1953.6 | 21,800 |

Above all, however, it is an 'event stratigraphy', in other words it is the *events* and not the boundaries between the events that are specifically designated. An event stratigraphic approach to the subdivision of the Last Termination acknowledges the fact that the stratigraphic boundaries marking the onset and ending of a climatic event may well be diachronous, depending on the sensitivity of the sites under consideration and on the local responses to that event. However, as it is the climatic *events* that are the key elements of the scheme, rather than the boundaries between those events, time-transgression no longer constitutes a major problem in terms of stratigraphic subdivision. Indeed, the approach can readily accommodate the fact that time-transgression is a real feature of the environmental systems upon which the event stratigraphy is based.

It is important to stress that what is being proposed here is *not* the replacement of one chronostratigraphic scheme (i.e. Mangerud *et al.*, 1974) with another. In applying the event-stratigraphy, we are inviting Quaternary scientists to adopt an inductive approach to stratigraphic subdivision, the initial stage of which is to identify local events or sequences of events at key sites on the basis of independent evidence. The second stage is to correlate these site-specific records with the type sequence, i.e. the GRIP oxygen isotope profile, on the basis of what are considered to be comparable major events. The third step (which is perhaps the most difficult, but perhaps also most important) is to use independent dating evidence to establish the degree of synchroneity between local and GRIP events, (Table 1). In this way, it may prove possible to establish time-lags and, by implication, feedback-related processes, between different parts of the climate system. Examples of the use of an event-stratigraphic approach in the subdivision of the Last Termination can be found in Asioli, Trincardi, Lowe and Oldfield (1999) and Lowe *et al.* (1999).

## 5. Wider applications of the event stratigraphy

Although the event stratigraphy described above has been specifically developed for the period of the Last Termination, there is no logical or practical reason why the concept should not be extended to include younger or older parts of the GRIP ice core record. With regard to the Holocene, it is not possible to follow the top-down, hierarchical approach to stratigraphic subdivision that was described above, as the magnitude and duration of events are generally much smaller, and hence the isotopic profile cannot easily be divided into a sequence of stadials and interstadials. However, clearly-defined 'events' can be recognised in the GRIP ice core, several of which appear to have hemispherical significance, and these can be designated on the basis of age in GRIP ice core years and prefixed by 'GH-'. In this way, the GRIP isotopic profile as a type or reference section for the North Atlantic region can be extended at least into the early part of the Holocene. For example, proxy records from around the North Atlantic region show evidence of a short-lived but clearly marked episode of climatic deterioration very early in the Holocene, an episode that has been termed the 'Preboreal Oscillation' (Björck *et al.*, 1996 Björck *et al.*, 1997). This period, however, was one of significantly increasing atmospheric $^{14}C$ content, and its $^{14}C$ year 'timespan' appears to have been more than twice as long as its length in (real) calendar years. This, together with its short duration, makes the cooling event very difficult to define in chronostratigraphic terms. Nevertheless, this climatic downturn is almost certainly reflected in a markedly colder 'event' in the oxygen isotope signal from the GRIP core centred on 11.2 k GRIP yrs BP (Fig. 2B). We therefore term this the 'GH (Greenland Holocene)-11.2

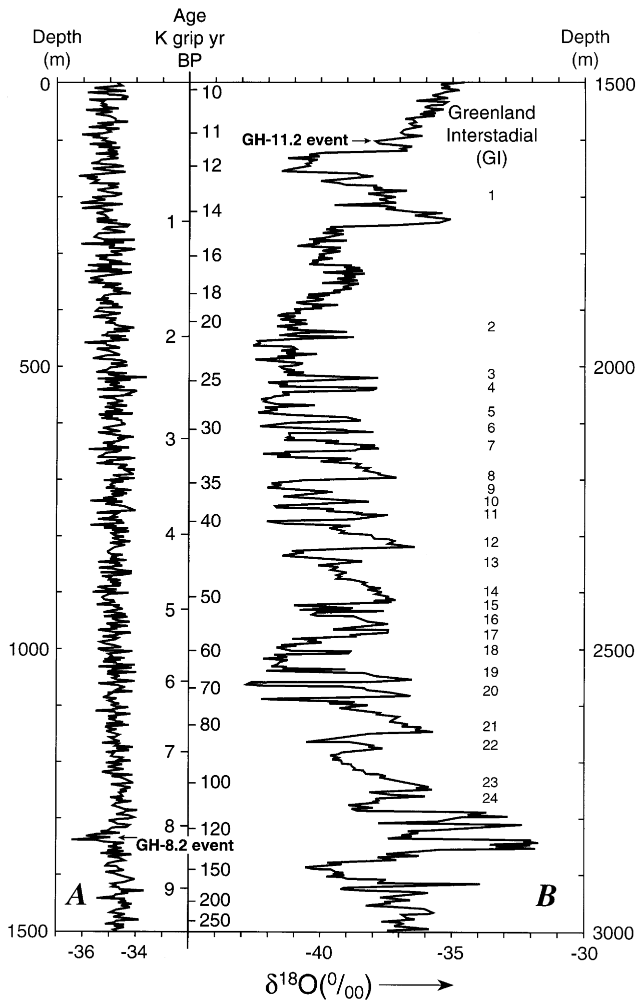


Fig. 2. The continuous GRIP $\delta^{18}O$ record plotted in two sections on a linear depth scale (after Dansgaard *et al.*, 1993): (A) from the ice surface to 1500 metres; (B) from 1500 to 3000 metres depth. The isotopically-defined Greenland Interstadial (GI) events are shown to the right of the $\delta^{18}O$. Also shown are the GH-8.2 k BP event (section A) and the GH-11.2 event (section B).

event'. Other short-lived isotopic events are apparent in the Holocene GRIP record, of which the 8.2 k GRIP yr cooling event ('GH-8.2 event') is perhaps the best known (Dansgaard *et al.*, 1993; Alley *et al.*, 1998; Klitgaard-Kristensen *et al.*, 1998: Fig. 2A), although it must be acknowledged that the climatic significance of many of these often subtle signals is, at present, rather less clear. Hence, while the potential is clearly there, an event stratigraphy for the middle and later Holocene based on the GRIP $\delta^{18}O$ profile cannot be fully developed until a better understanding of the small-scale variability of the GRIP oxygen isotope ratios is achieved, and their significance is elaborated by more secure correlations with marine and terrestrial records.

The notion of the GRIP oxygen isotope record as a regional or, indeed, hemispherical stratotype for an 'event stratigraphy' is more readily applicable to the earlier parts of the Last Cold Stage, and perhaps also to the Last Interglacial (Fig. 2B). Johnsen et al. (1992) identified a further 22 isotopically defined interstadials ('Dansgaard-Oeschger events') in the GRIP core below Greenland Interstadial 2 (GI-2) extending over 80 k GRIP yr BP. As was the case during the Last Termination, the climatic fluctuations throughout this entire time interval appear to have been extremely rapid, certainly during periods of warming, and relatively short-lived. This is a much more highly resolved climatic record than that, for example, represented in long European pollen sequences (e.g. Behre, 1989; Beaulieu & Reille, 1992), or in isotopic or biological records from North Atlantic sediment (e.g. Ruddiman, 1987). The GRIP record therefore constitutes the best available stratotype against which climatic change during the course of the Last Cold Stage, as reflected in both terrestrial and marine records, can be compared (e.g. Bond *et al.*, 1993; Dansgaard *et al.*, 1993). Similarly, the climatic sequence during the Last Interglacial as reflected in the GRIP oxygen isotope record (Fig. 3), although at present not altogether satisfactorily resolved due o uncertainties relating to the integrity of the basal ice record (Johnsen *et al.*, 1997), could possibly form the basis for an event stratigraphy. Future analyses of ice from the ongoing NORDGRIP corings, some 320 km NNW of Summit, into what is believed to be relatively undisturbed ice older than marine oxygen isotope stage 4 (Dahl-Jensen *et al.*, 1997), may therefore ultimately allow an extension of the GRIP event stratigraphy back to the Last Interglacial.

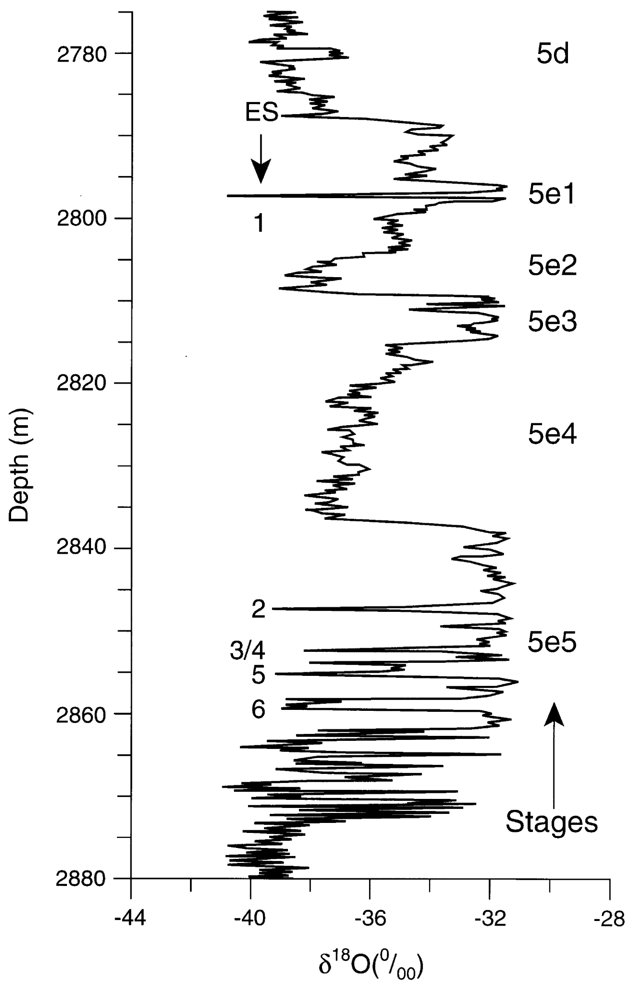


Fig. 3. High-resolution $\delta^{18}O$ profile spanning the Last (Eemian) Interglacial. The numbers to the left of the curve show the $\delta^{18}O$ 'spikes' representing distinctive isotopically defined Eemian 'events' (ES-1 to ES-6), while the numbers to the right indicate Eemian isotopic substages (after Johnsen *et al.*, 1997)

## 6. Conclusion

It is the recommendation of the INTIMATE group that the oxygen isotope signal from the GRIP Greenland ice core should constitute the stratotype for the Last Termination, and that this episode can be resolved into a sequence of isotopically-defined climatic events (stadials and interstadials). The terms GI-1 and GS-1 should replace the NW European biostratigraphically and chronostratigraphically-based terminology (Bølling, Allerød, Older and Younger Dryas) that has been employed hitherto in the subdivision and correlation of sequences from this time interval. It is also suggested that the event stratigraphy as reflected in the isotopic profile in the GRIP ice core can be extended to encompass the early Holocene, the entire Last Cold Stage, and perhaps, in due course, also the Last Interglacial.

## Acknowledgements

We would like to thank the Editor of *Quaternary Science Reviews*, Professor Jim Rose, for inviting us to contribute this Viewpoint paper, and for his constructive critical appraisal of an earlier draft of the manuscript. We also wish to express our gratitude to the participants in the INTIMATE Workshop held at Höör, Sweden, in September 1997, whose ideas form the basis for this, and for the previous (Björck *et al*., 1998) paper. We thank Justin Jacyno for cartographic assistance, and the INQUA Palaeoclimatic Commission for funding the INTIMATE programme.

## References


Alley, R. B., Meese, D. A., Shuman, C. A., Gow, A. J., Taylor, K. C., Grootes, P. M., White, J. W. C., Ram, M., Waddington, E. D., Mayewski, P. A., & Zielinski, G. A. (1993). Abrupt increase in Greenland snow accumulation at the end of the Younger Dryas event. *Nature*, *362*, 527–529.

Alley, R. B., Mayewski, P. A., Sowers, T., Stuiver, M., Taylor, K. C., & Clark, P. U. (1997). Holocene climate instability: A prominent widespread event 8200 yr ago. *Geology*, *25*, 483–486.

Ammann, B., & Lotter, A. F. (1989). Late-glacial radiocarbon and palynostratigraphy on the Swiss Plateau. *Boreas*, *18*, 109–126.

Andersson, G. (1896). *Svenska växtvärldens historia*. Stockholm: P.A. Norsted and B. Söner.

Asioli, A., Trincardi, F., Lowe, J.J., & Oldfield, F. (1999). Short-term climate changes during the Last-Glacial-Holocene transition: Comparison between Mediterranean and North Atlantic records. *Journal of Quaternary Science, 14*, in press.

Beaulieu, J. L. de, & Reille, M. (1992). The last climatic cycle at La Grande Pile (Vosges, France): a new pollen profile. *Quaternary Science Reviews*, *11*, 431–438.

Behre, K. -E. (1989). Biostratigraphy of the last glacial period in Europe. *Quaternary Science Reviews*, *8*, 25–44.

Björck, S., Kromer, B., Johnsen, S., Bennike, O., Hammarlund, D., Lemdahl, G., Possnert, G., Rasmussen, T. L., Wohlfarth, B., Hammer, C. U., & Spurk, M. (1996). Synchronised terrestrial-atmospheric deglacial records around the North Atlantic. *Science*, *274*, 1155–1160.

Björck, S., Rundgren, M., Ingolfsson, O., & Funder, S. (1997). The Preboreal oscillation around the Nordic Seas: terrestrial and lacustrine responses. *Journal of Quaternary Science*, *12*, 455–464.

Björck, S., Walker, M.J.C., Cwynar, L.C., Johnsen, S., Knudsen, K-L., Lowe, J.J., Wohlfarth, B., & INTIMATE Members (1998). An event stratigraphy for the Last Termination in the North Atlantic region based on the Greenland ice-core record: A proposal by the INTIMATE group. *Journal of Quaternary Science*, *13*, 283–292.

Bond, G., Broecker, W., Johnsen, S. J., McManus, J., Labeyrie, L., Jouzel, J., & Bonani, G. (1993). Correlation between climatic records from North Atlantic sediments and Greenland ice. *Nature*, *365*, 143–147.

Bowen, D. Q. (1978). *Quaternary geology*. Oxford: Pergamon.

Broecker, W.S. (1984). Terminations. In A. Berger, J. Imbrie, J. Hays, G. Kukla & B. Saltzman, *Milankovitch & climate* Dordrecht: Reidel. (pp. 687–698).

Coope, G. R., Lemdahl, G., Lowe, J. J., & Walkling, A. (1998). Temperature gradients in northern Europe during the last glacial-Holocene transition (14–9 $^{14}$C kyr BP) interpreted from coleopteran assemblages. *Journal of Quaternary Science*, *13*, 419–443.

Dahl-Jensen, D., Gundestrup, N. S., Keller, K., Johnsen, S. J., Goineni, S. P., Allen, C. T., Chuah, T. S., Miller, H., Kipfstuhl, S., & Waddington, E. D. (1997). A search in north Greenland for a new ice-core drill site. *Journal of Glaciology*, *43*, 300–306.

Dansgaard, W., Johnsen, S. J., Clausen, H. B., Dahl-Jensen, D., Gundestrup, N. S., Hammer, C. U., Hvidberg, C. S., Steffensen, J. P., Sveinbjörnsdóttir, A. E., Jouzel, J., & Bond, G. (1993). Evidence for general instablity of past climate from a 250-kyr ice – core record. *Nature*, *364*, 218–220.

Hammer, C. U., Andersen, K. K., Clausen, H. B., Dahl-Jensen, D., Hvidberg, C. S., & Iversen, P. (1997). *The stratigraphic dating of the GRIP ice core*. Special report of the Geophysical Department, Niels Bohr Institute for Astronomy, Physics and Geophysics, University of Copenhagen.

Hartz, N., & Milthers, V. (1901). Det senglaciale Ler i Allerød Teglværksgrav. *Meddelelser Dansk Geologisk Foreningen*, *8*, 31–60.

Hedberg, H.D. (Ed.). (1970). International stratigraphic guide. New York: Wiley.

Hughen, K. A., Overpeck, J. T., Peterson, L. C., & Trumbore, S. (1996). Rapid climate changes in the tropical North Atlantic region during the last deglaciation. *Nature*, *380*, 51–54.

Jessen, K. (1935). Archaeological dating in the history of North Jutland's vegetation. *Acta Archaeologica*, *5*, 185–214.

Jessen, K. (1938). Some West Baltic pollen diagrams. *Quartär*, *1*, 14–139.

Johnsen, S., Clausen, H. B., Dansgaard, W., Fuhrer, K., Gundestrup, N., Hammer, C. U., Iversen, P., Jouzel, J., Stauffer, B., & Steffensen, J. P. (1992). Irregular interstadials recorded in a new Greenland ice core. *Nature*, *359*, 311–313.

Johnsen, S.J., Clausen, H.B., Dansgaard, W., Gundestrup, N.S., Hammer, C.U., Andersen, U.A., Andersen, K.K., Hvidberg, C.S., Dahl-Jensen, D., Steffensen, J.P., Shoji, H., Sveinbjörnsdóttir, A.E., White, J., Jouzel, J., & Fisher, D. (1997). The $\delta^{18}$O record along the Greenland Ice core Project deep ice core and the problem of possible Eemian climatic instability. *Journal of Geophysical Research*, 102, 26,397–26,410.

Kitagawa, H., & van der Plicht, J. (1998). Atmospheric radiocarbon calibration to 45,000 yr BP: Lateglacial fluctuations and cosmogenic isotope production. *Science*, *279*, 1187–1190.

Klitgaard-Kristensen, D., Sejrup, H. P., Haflidason, H., Johnsen, S., & Spurk, M. (1998). A regional 8200 cal. yr BP cooling event in northwest Europe, induced by final stages of Laurentide deglaciation?. *Journal of Quaternary Science*, *13*, 165–169.

Lowe, J.J. (1991). Stratigraphic resolution and radiocarbon dating of Late Devensian sediments. In *Radiocarbon dating: Recent applications and future potential, Quaternary Proceedings*, vol. 1 (pp. 19–26). Cambridge: Quaternary Research Association.

Lowe, J.J., & Walker, M.J.C. (1997). *Reconstructing Quaternary Environments* (2nd ed.). London: Addison-Wesley-Longman.

Lowe, J. J., Birks, H. H., Coope, G. R., Harkness, D. D., Mayle, F. E., Turney, C. S. M., Walker, M. J. C., & Sheldrick, C. (1999). The chronology of ecosystem responses to climate variations during the Last Glacial-Interglacial Transition: Towards an event stratigraphy for the British Isles. *Quarterly Journal of the Geological Society of London,*, *156*, 397–410.

Mangerud, J., Andersen, S. T., Berglund, B. E., & Donner, J. J. (1974). Quaternary stratigraphy of Norden: A proposal for terminology and classification. *Boreas*, *3*, 109–128.

North American Commission on Stratigraphic Nomenclature (1983). North American Stratigraphic Code. *American Association of Petroleum Geologists Bulletin*, *67*, 841–875.

Salvador, A. (Ed.) (1994). *International stratigraphic guide: A guide to stratigraphic classification, terminology and procedure* (2nd ed). International Union of Geological Sciences and Geological Society of America, Inc.

Shackleton, N. J., & Opdyke, N. D. (1973). Oxygen isotope and palaeomagnetic stratigraphy of equatorial Pacific core V28-238: Oxygen isotope temperatures and ice volumes on a $10^5$ and $10^6$ year timescale. *Quaternary Research*, *3*, 39–55.

Shackleton, N. J., Berger, A., & Peltier, W. R. (1990). An alternative astronomical calibration of the lower Pleistocene timescale based on ODP Site 677. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, *81*, 251–261.

Rose, J. (1989). Stadial type sections in the British Quaternary. In J. Rose, & C. Schlüchter, *Quaternary type sections: Imagination or reality*. Rotterdam: (pp. 45-67).

Ruddiman, W.F. (1987). Northern oceans. In W.F. Ruddiman & H.E. Wright Jr, *The geology of North America*. vol. K-3. *North America and adjacent oceans during The Last Deglaciation* (pp. 137–153). Boulder, Colorado: Geological Society of America.

Taylor, K. C., Hammer, C. U., Alley, R. B., Clausen, H. B., Dahl-Jensen, D., Gow, A. J., Gundestrup, N. S., Kipfstuhl, J., Moore, J. C., & Waddington, E. D. (1993). Electrical conductivity measurements from the GISP2 and GRIP Greenland ice cores. *Nature*, *366*, 549–552.

Taylor, K. C., Mayewski, P. A., Alley, R. B., Brook, E. J., Gow, A. J., Grootes, P. M., Meese, D. A., Saltzman, B., Severinghaus, J. P., Twickler, M. S., White, J. W. C., Whitlow, S., & Zielinski, G. A. (1997). The Holocene-Younger Dryas transition recorded at Summit. *Greenland. Science*, *278*, 825–827.

West, R.G. (1989). The use of type localities and type sections in the Quaternary, with especial reference to East Anglia. In J. Rose, & C. Schlüchter, *Quaternary type sections: Imagination or reality* (pp. 3–10). Rotterdam: Balkema.

Whittaker, A., Cope, J. W. C., Cowie, J. W., Gibbons, W., Hailwood, E. A., House, M. R., Jenkins, G. D., Rawson, P. F., Rushton, A. W. A., Smith, D. G., Thomas, A. T., & Wimbledon, W. A. (1991). A guide to stratigraphical procedure. *Journal of the Geological Society, London*, *148*, 813–824.

Witte, H. J. L., Coope, G. R., Lemdahl, G., & Lowe, J. J. (1998). Regression coefficients of thermal gradients in northwestern Europe during the last glacial-Holocene transition using beetle MCR data. *Journal of Quaternary Science*, *13*, 435–446.