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Synchronisation of palaeoenvironmental events in the North Atlantic region during the Last Termination: a revised protocol recommended by the INTIMATE group

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Abstract

The North Atlantic INTIMATE group of the INQUA Palaeoclimate Commission has previously recommended an Event Stratigraphy approach for the synchronisation of records of the Last Termination using the Greenland GRIP isotopic record as the regional stratotype and INTCAL98 for the calibration of radiocarbon dates [Lowe, J.J., Hoek, W., INTIMATE Group, 2001. Inter-regional correlation of palaeoclimatic records for the Last Glacial-Interglacial Transition: a protocol for improved precision recommended by the INTIMATE project group. Quaternary Science Reviews 20, 1175–1187]. Here, we present a revised protocol for time-stratigraphic correlation in the North Atlantic region over a more extended time period (30–8 ka). This employs the new NGRIP isotopic record and associated Greenland Ice Core Chronology 2005 (GICC05) as the regional stratotype, INTCAL04 for the calibration of radiocarbon dates, Bayesian-based statistical procedures for the construction of age models, and tephrochronology to validate correlations between regional site records.

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1. Introduction

The goal of the North Atlantic INTIMATE project,[2] inaugurated in 1995 (Walker et al., 2001a), is to synthesise ice-core, marine and terrestrial records that span the Last Termination (ca 22–11.5 ka). The key objective was to determine whether abrupt climatic changes during that period, as reflected in a range of proxy records, were regionally synchronous or whether there were significant 'leads' and 'lags' between the atmospheric, marine, terrestrial and cryospheric realms. Establishing the precise order of events during the Last Termination has proved an elusive goal, however, principally because limitations in the dating tools currently available inhibit the temporal resolution of the individual climatic episodes (Björck et al., 1998; Walker et al., 1999; Lowe et al., 2001).

The Greenland ice-core records have demonstrated beyond reasonable doubt that during the Last Termination marked climatic shifts occurred within a matter of decades—sometimes even in less than 20 years (Dansgaard et al., 1993; Taylor et al., 1997; Rasmussen et al., 2006). Few geological dating techniques can resolve past environmental events at this level of precision. In the case of radiocarbon dating, which is the most widely employed method for dating events within the last 50 ka, a centennial

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[2] INTIMATE: INtegration of Ice-core, MArine and TErrestrial records of the North Atlantic is a core project of the INQUA Palaeoclimate Commission (http://www.geo.uu.nl/fg/intimate).

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precision is difficult to achieve, even for Holocene records (e.g. Telford et al., 2004a, b), while the 'true' errors associated with radiocarbon dates of Last Termination age are frequently of millennial magnitude (see Lowe et al., 2007). Alternative dating approaches, such as varve chronology (e.g. Hajdas et al., 1995; Hughen et al., 1998a, b; Litt et al., 2001) and dendrochronology (e.g. Friedrich et al., 2001; Kromer et al., 2004), can provide more highly resolved time-series, but these techniques can only be used in relatively rare circumstances and they are also affected by dating uncertainty arising from counting errors. Developing a dating strategy for terrestrial and marine sequences that can generate chronologies of comparable precision to the ice-core sequence is one of the principal challenges confronting scientists working on the Last Termination.

A second major difficulty concerns the wide usage of climatostratigraphic terms that were originally defined with specific reference to events in Scandinavia, such as 'Younger Dryas', 'Bølling' and 'Allerød' (see Björck et al., 1998; Walker et al., 1999 for fuller discussion). This practice has tended to assume compatibility and synchroneity of events over wide areas, a scenario that might be plausible but which has been somewhat undermined by the growing body of evidence for diachronous climatic shifts in some proxy records from the Last Termination (e.g. Coope et al., 1998; Blockley et al., 2004). Matters have been further complicated by possible differences in the timing of major climatic changes between mainland Europe and other regions (e.g. Nakagawa et al., 2003; Björck, 2006; Turney et al., 2006a; Blockley et al., 2008). In addition, it now seems that a persistent phase-lagged climatic pattern between the two polar regions was present throughout the last cold stage (Stocker and Johnsen, 2003; EPICA Community Members, 2006). In essence, therefore, terms such as 'Younger Dryas' and 'Bølling-Allerød' cannot have the same climatostratigraphic meaning in both Antarctica and the North Atlantic region, nor can they be used, *sensu stricto*, as chronostratigraphic units, because of the time-transgressive nature of climate change (Walker, 1995; Björck et al., 1998). This underlines the need for greater clarity in the definition and employment of climatostratigraphic terms, and for improved precision in the dating and correlation of records. Imprecise terminology and chronology blurs the palaeoenvironmental picture, and hence inhibits the testing of competing theories about the mechanisms driving abrupt climatic change during the Last Termination.

In order to standardise stratigraphical procedures and to clarify the sequence, timing and duration of events during the Last Termination, INTIMATE advocated an Event Stratigraphy approach, using the GRIP ss08c isotopic record as the regional stratotype, as this was considered to provide the best-resolved and most complete template for climatic events during the Last Termination in the North Atlantic region. Other records based on independently determined palaeoclimatic reconstructions and age models from the terrestrial and marine realms could then be compared to the ice-core stratotype. In this scheme, the GRIP isotopic notation replaced the conventional (Nordic) chrono/climatostratigraphic terms as the standard for comparison (Björck et al., 1998; Walker et al., 1999).

It is important to clarify the rationale that underlies this Event Stratigraphy approach, as there has been a degree of misunderstanding in some quarters. The most widespread misconception is that INTIMATE recommended the replacement of regional and/or conventional terms, such as 'Younger Dryas' and 'Bølling', with the GRIP isotope terminology in the formal naming of regionally based stratigraphical units. This is not the case. Rather, INTIMATE recommended that all site records should initially be designated using the appropriate local terminology, and that the timing and duration of local or regional climatic/environmental events be established independently of the ice-core record. Subsequent time-stratigraphic correlation with the Greenland stratotype should take account of the statistical uncertainties inherent in the age models employed (e.g. Lowe et al., 1999; Björck et al., 2003; Alloway et al., 2007; Vescovi et al., 2007) and, wherever possible, should be validated using independent techniques, such as tephrochronology (Davies et al., 2002; and see below). Moreover, it was recognised that the Greenland ice-core record may not provide a suitable template for regions that have experienced a quite different sequence of climatic events during the Last Termination. For records from Australasia, for example, comparison with the EPICA Dome C record may be more practical (Alloway et al., 2007).

The North Atlantic Event Stratigraphy scheme was reassessed at the 8th INTIMATE International Workshop held in Iceland in 2005. The consensus at that meeting was that it continues to provide the most robust framework for correlating high-resolution stratigraphic records from the Last Termination. However, revision of the scheme was deemed necessary for five principal reasons. First, a new Greenland ice-core record from NorthGRIP (NGRIP), with a chronology of significantly improved temporal resolution and precision (Greenland Ice Core Chronology 2005 (GICC05)) is now available. Second, the INTCAL98 calibration has been superseded by INTCAL04, which includes a more comprehensive database for marine radiocarbon reservoir errors. Third, a range of statistical techniques (notably Bayesisan methods) are now routinely being employed in the calibration of radiocarbon data-series and in the testing of age models. Fourth, considerable progress has been made in the detection of tephra horizons in both marine and terrestrial sediments, and also in ice cores, including both visible and non-visible fine ash layers ('cryptotephras' or 'microtephras'). Indeed, in some regions of the world, there is now a number of time-parallel markers that can be used to correlate stratigraphic records. Fifth, the Event Stratigraphy approach has recently been adopted by the Australasian INTIMATE group, with the time-span extended to 30 ka to include a marked warming event that commenced ca 28 ka (Alloway et al., 2007). Since the longer-term objective of the INTIMATE project is to allow high-resolution comparison of records for the Last Termination at a global scale, it would seem logical to extend the North Atlantic record back beyond the Last Termination *sensu stricto* in line with the procedure adopted by the Australasian INTIMATE group.

Here, we present a revised Event Stratigraphy scheme for the North Atlantic region which takes account of these recent developments.

2. The new GICC05 chronology and NGRIP stratoype

The NGRIP ice core project was initiated in 1996 primarily to resolve discrepancies between the GRIP and GISP2 records for the Eemian and early last glacial periods; however, continuous high-resolution analysis of a range of proxy data were subsequently carried out on the entire glacial NGRIP core section, with some records extending up through the Holocene to the present ice surface. The GRIP and NGRIP oxygen isotope record are generally very similar, and a chronology for the NGRIP record was therefore initially derived by tuning the NGRIP record to the GRIP ss09sea chronology (Johnsen et al., 2001) using abrupt inflections in the oxygen isotope trace as marker events (North Greenland Ice Core Project Members, 2004). Subsequent analysis has shown, however, that the GRIP ss09sea chronology is relatively imprecise for the Last Termination, because it is based partly on an ice accumulation model that does not match the observations well in the Lateglacial part of the record (Svensson et al., 2006). Also the uncertainty of the age model was not quantified, but is believed to be at least centennial in magnitude (see Blockley et al., 2004). By contrast, care has been taken to quantify the systematic counting errors in the construction of the new NGRIP record, providing the basis for a much improved chronology for events in Greenland.

A new Greenland timescale, GICC05 has been constructed by combining the NGRIP, GRIP and DYE-3 ice-core records. The GICC05 age model is still being extended and refined, but the section presented here, spanning the last 30 ka, is not likely to be revised until additional data become available. In this paper, the ages derived from the new ice-core age model are expressed as 'ka GICC05 b2k', b2k being years before 2000 AD, which is the temporal datum chosen by the NGRIP team for reporting ice core age estimates (Rasmussen et al., 2006). Radiocarbon age estimates are expressed in ^{14}C years BP (defined as 1950 AD), calibrated radiocarbon ages are expressed as 'cal BP' and calendar ages based on other methods or unrelated to a specific dating method are denoted as ka (see IUPAC-IUGS Task Group 2006; Rose 2007).

In the part of the GICC05 record that is younger than 7.9 ka GICC05 b2k, annual ice layers have been identified on the basis of δ^{18}O and δD variations which reflect the seasonal temperature cycle (Vinther et al., 2006). For the older parts of the record, discrimination of annual ice layers is based on high-resolution continuous flow analysis of the impurities contained within the ice, acidity measurements, and the visual stratigraphy record of the NGRIP core (Andersen et al., 2006; Rasmussen et al., 2006). Counting of annual layers was performed independently by several investigators and the results merged by consensus. Discrepancies between individual records are mainly attributed to divergence of views on whether some occasional subtle features represent annual layers or not. The magnitude of the operator differences provides a quantitative index of the degree of uncertainty in the GICC05 age model. This is termed the 'maximum counting error' (MCE), which is estimated to be up to 2% for the early Holocene part of the record, and about 3% for older sections. An overlapping zone spanning several hundred ice-core years provided a check on counting consistency when switching analyses between the δ^{18}O and impurity records, while a prominent volcanic horizon within the 8.2 ka cold event, clearly identifiable in all of the Greenland records, provides an unambiguous tie-point for matching the DYE-3 δ^{18}O chronology with the GRIP and NGRIP impurity data (Rasmussen et al., 2006).

While the GICC05 chronology is not without its problems (e.g. consistency in determining the criteria employed for defining annual layers), it nevertheless offers distinct advantages over the previously published GRIP and GISP2 age models. The entire record is based on layer-by-layer counting, the counting errors are quantified more robustly, and the analyses are based on a wider range of analytical data, examined simultaneously at higher stratigraphical resolution. Also, during relatively warm climate conditions, several of the individual proxy records exhibit a consistent order of change over successive ice layers, which gives increased confidence in their interpretation as indicators of seasonal differences (Rasmussen et al., 2006). A further feature of the high-resolution GICC05 chronology is that it offers a basis for estimating, with a relatively high degree of precision, the *durations* of successive warm and cold events, since counts of the number of annual ice layers within each interval can be undertaken *ab initio* with a zero maximum counting error at the start of the counting process.

The GICC05 chronology for the sequence of isotopically defined climatic events that affected Greenland during the last 30 ka is provided in Fig. 1, while GICC05 age estimates (with maximum counting errors) for the transitions between the events are listed in Table 1. The INTIMATE group recommendation is that GICC05 should replace the GRIP ss08c age model as the chronology that underpins the ice-core stratotype for the Last Termination in the North Atlantic region. We anticipate, however, that the Event Stratigraphy scheme and the associated ice-core age estimates will be further refined in due course. The Preboreal Oscillation (PBO), for example, is difficult to define precisely on available evidence and hence has not yet been assigned age estimates, while low amplitude differences between the GRIP and NGRIP records for isotopic

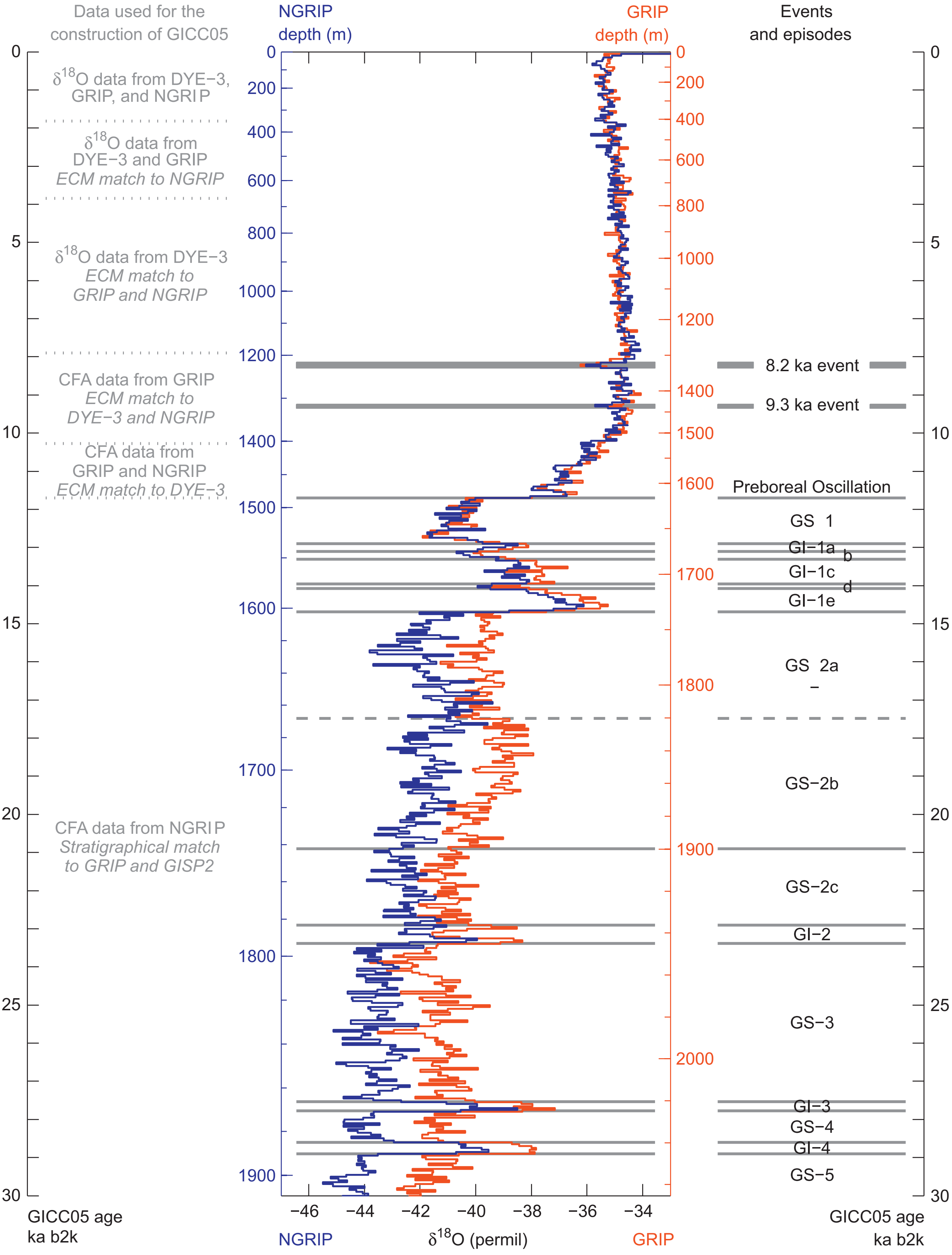

Fig. 1. Comparison of the δ^{18}O records for the NGRIP and GRIP ice-core records for the last 30,000 years at a 50-year resolution.

Table 1
The GICC05 chronology for key climatic events during the interval ca 30–8 ka GICC05 b2k

Events	Current recommendation				Former recommendation	
	Depth in NGRIP core (m)	GICC05 age b2k (note[a])	Max. count error (MCE)	Depth in GRIP core (m)	Depth in GRIP core (m)	ss08c age b2k (note[a])
8.2 ka BP event	1219.47[b,c]	8140	45	1325.11[b,d]		
Volcanic peak inside 8.2 ka	1228.67[c]	8236	47	1334.04		
8.2 ka BP event	1234.78[b,c]	8300	49	1340.50[b,d]		
9.3 ka BP event	1322.88[b,c]	9240	68	1432.43[b]		
9.3 ka BP event	1331.65[b,c]	9350	70	1442.10[b]		
PBO event						
Start of Holocene	1492.45[e]	11703	99	1624.27	1623.6	11550
Start of GS-1	1526.52[e]	12896	138	1662.41[g]	1661.5	12700
Start of GI-1a	1534.5[f]	13099	143		1671.7	12950
Start of GI-1b	1542.1[f]	13311	149		1680.5	13200
Start of GI-1c	1570.5[f]	13954	165		1713.7	13950
Start of GI-1d	1574.80[e]	14075	169	1718.50[g]	1719.2	14100
Start of GI-1e	1604.64[e]	14692	186	1753.39[g]	1753.4	14750
Start of GS-2a	Feature not clear in NGRIP profile				1823.7	16950
Start of GS-2b	1745.31	20900[h,i]	482	1899.70[i]	1901.3	19550
Start of GS-2c	1783.62	22900[i]	573	1940.28[i]	1939.1	21250
Start of GI-2	1794.08	23340[i,j]	596	1950.46[i]	1953.6	21850
Start of GS-3	1861.69	27540[i]	822	2018.09[i]		
Start of GI-3	1869.12	27780[i]	832	2025.39[i]		
Start of GS-4	1882.62	28600[i]	887	2037.70[i]		
Start of GI-4	1891.57	28900[i]	898	2046.05[i]		

Note: Defining the onset and termination of climatic events can be an ambiguous task—the higher the temporal resolution at which this is attempted, the more difficult it becomes. In the NGRIP record, for example, the onset and termination of events GI-1e and GS-1 are defined in Rasmussen et al. (2006) using deuterium excess data, because the deuterium excess is the clearest indicator of climate change. Changes in deuterium excess reflect major reorganizations of atmospheric circulation; these are generally followed by more gradual changes in temperature. Many of the transition depths in Table 1 have been defined at the mid-point of the $\delta^{18}O$ slopes rather than using the deuterium excess data, and should therefore be regarded as preliminary markers. The transitions denoted by deuterium excess signals most likely precede changes in temperature and vegetation recorded in other archives.

[a] b2k, before 2000 AD.

[b] Derived from Rasmussen et al. (2008), in which the events are defined using combined DYE-3, GRIP and NGRIP data on the GICC05 timescale. The durations of events are shown as the maximum estimates, obtained using the first onset and the last endpoints.

[c] NGRIP1 depths used for 8.2 and 9.3 ka events. NGRIP2 depths used otherwise. To convert these NGRIP1 depths to NGRIP2 depths, subtract 0.43 m.

[d] Thomas et al. (2007) defines the onset at GRIP depth 1340.12 m/8297 b2k and the end point at GRIP depth 1324.77 m/8136 b2k.

[e] From Rasmussen et al. (2006).

[f] GRIP depths from Björck et al. (1998), transferred to NGRIP depths using the volcanic markers of Rasmussen et al. (2006).

[g] NGRIP depths transferred to GRIP using the volcanic markers of Rasmussen et al. (2006).

[h] Uncertainty estimated to 100 years.

[i] Defined from midpoint of $\delta^{18}O$ transition in combined NGRIP, GRIP, and GISP2 records following the approach of Andersen et al. (2006). NGRIP depths obtained from the GICC05 depth–age relation, transferred to GRIP depths using the synchronization of Rasmussen et al. (2008). Uncertainty up to 40 years

[j] Uncertainty estimated to 60 years.

event GS-2 are currently difficult to reconcile (Rasmussen et al., 2008).

3. Synchronising marine and terrestrial records with the NGRIP stratotype

As noted above, the GICC05 age model for the last ca 30 ka enables climatic events reflected in the ice-core record to be resolved on an annual to decadal timescale, a level of temporal resolution that currently cannot be achieved using radiocarbon dating because of the wide error margins on most age estimates. The statistical uncertainties associated with radiocarbon dates are a compound effect of (a) analytical limits to the precision of measurement of radiocarbon activity; (b) sample-specific factors, such as isotopic fractionation and fossil or 'old' carbon recycling; (c) site-specific factors, such as the influence of hard-water or marine reservoir effects and (d) a lack of precision in the calibration models currently used to convert radiocarbon dates to calendar time (e.g. Hughen et al., 2004; Guilderson et al., 2005). It is rare indeed for all four sources of uncertainty to be factored into specified error terms, not least because error sources (b) and (c) are frequently difficult to detect and/or to quantify. Furthermore, age–depth models based on stratigraphic series of radiocarbon dates commonly embody questionable assumptions, for example, a linear or other generalised sedimentation rate between dated horizons, or that individual age estimates are a true reflection of the

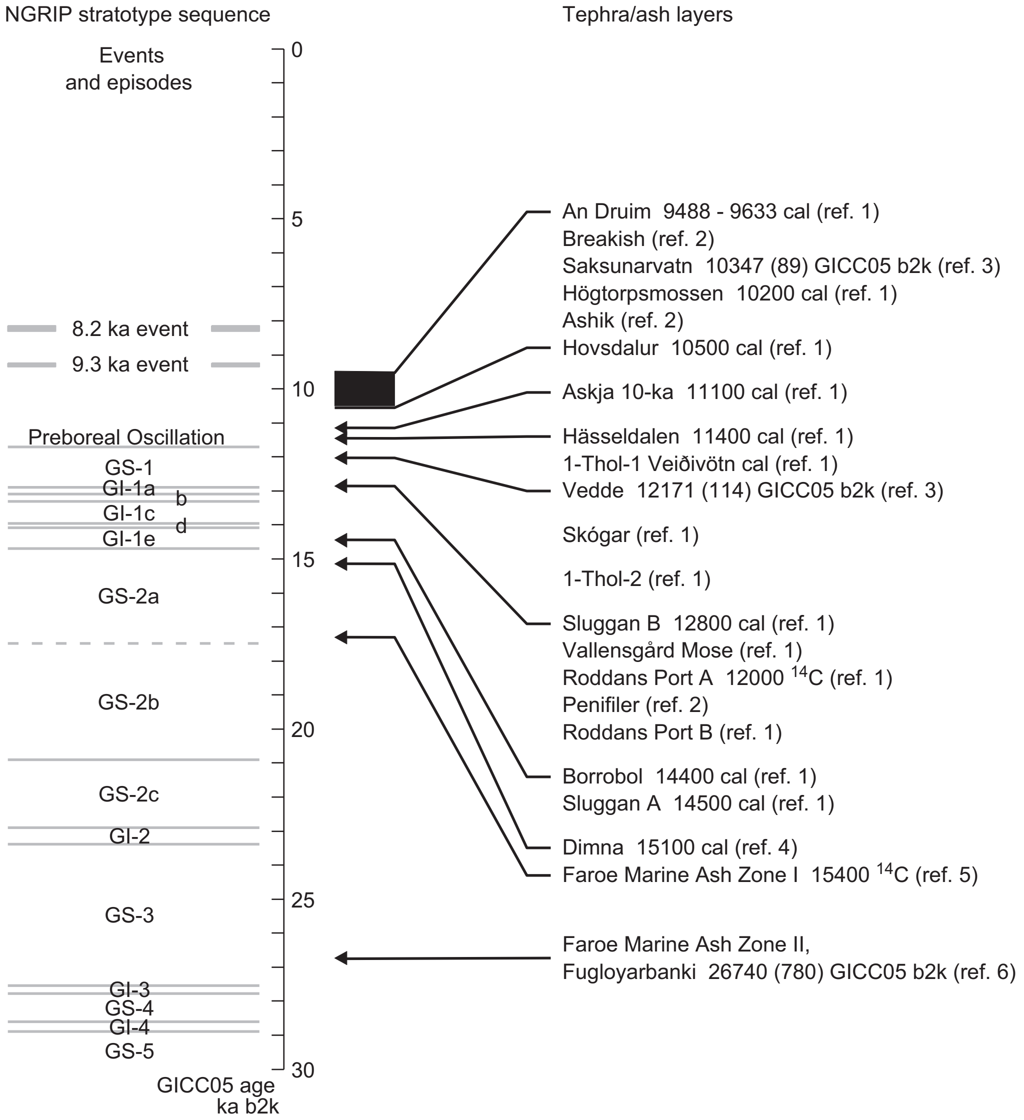

Fig. 2. The sequence of (mostly) non-visible distal volcanic ash layers of Icelandic origin in marine and terrestrial records from the North Atlantic region. The most recent age estimate published for each tephra layer is provided, with preference given to the GICC05 age (maximum counting errors given in brackets) were known. Radiocarbon-based ages are expressed in radiocarbon (14C) or calibrated radiocarbon (cal) ages according to published data. The stratigraphic order of some of the ashes may not be correct, since order of superposition has not yet been fully established, while the age estimates for some have large uncertainties. Ref. 1 = Turney et al. (2006c); Ref. 2 = Pyne-O'Donnell (2007); Ref. 3 = Rasmussen et al. (2006); Ref. 4 = Koren et al. (2008); Ref. 5 = Wastegård et al. (2006) and Ref. 6 = Svensson et al. (2006).

mean activity of the organic material within each dated horizon (Lowe et al., 2007). These difficulties notwithstanding, it is acknowledged that radiocarbon will continue to be the most widely used method for dating terrestrial and marine sequences from the Last Termination and the Holocene, and hence there is an imperative on the scientific community to generate radiocarbon-based time series of the highest quality. Here we examine some of the approaches that might be employed to achieve that aim.

3.1. Sample selection and pre-treatment

Radiocarbon dates are only as good as the materials that are being dated and, in recent years, attempts have been made both to design sampling strategies and develop more refined laboratory procedures that mitigate the effects of the intrinsic error sources outlined above (Hedges, 2001; Walker et al., 2001b). Obtaining sample material of the highest possible purity and integrity is clearly of paramount importance, and significant progress has been made, *inter alia*, in the extraction of compound-specific materials for dating, for example from marine sediments (Eglinton et al., 1997; Ohkouchi et al., 2003; Ingalis et al., 2004), and in the purification of insect chitin (Hodgins et al., 2001; Tripp et al., 2004) and bone (Bronk Ramsey et al., 2004; Higham et al., 2006) from terrestrial sites. These new approaches are key to the generation of high-precision radiocarbon chronologies for the Last Termination.

3.2. Development of improved radiocarbon calibration models

The internationally accepted standard for radiocarbon calibration, INTCAL04, provides reasonably precise age-calibrations back to ca 12.4 ka, the current upper limit of dendrochronologically based calibration (Reimer et al., 2004), but is much less precise for earlier intervals where the bases for calibration are less secure (Van der Plicht et al., 2004). There is also a significant divergence between several independently constructed calibration models for pre-Holocene intervals (Hughen et al., 2004; Chiu et al., 2005; Fairbanks et al., 2005; Balter, 2006; Turney et al., 2006b), while it is by no means certain that the INTCAL04 model provides the superior data. Important work is underway to extend dendro-based calibration beyond 12.4 ka by connecting to floating dendrochronological records preserved in sites in continental Europe (e.g. Kromer, 2004; Schaub et al., 2008), while fossil kauri trees in New Zealand offer the tantalising prospect of a continuous dendrochronological record extending back to beyond 50 ka (Palmer et al., 2006; Turney et al., in press). The latter investigation is still at an early stage, however, and it may be several years before a long dendro-based calibration curve which extends through the Last Termination becomes available.

3.3. Generating more comprehensive radiocarbon data-sets

Sites vary enormously in the manner in which organic detritus is recruited. For most marine and lacustrine sites there is likely to be a mix of material of different 'age' (radiocarbon activity) throughout the sediment sequence. The degree of variance in the radiocarbon activity from any single horizon (the radiocarbon 'inventory') is difficult to assess if only a small number of radiocarbon measurements is available. In such cases, the resulting age models can offer little more than 'rangefinder' dates. The greater the number of radiocarbon measurements used in site investigations, the better constrained will be the resulting age models and the more robustly they can be statistically tested for accuracy (Lowe et al., 2004; Blaauw and Christen, 2005; Heegard et al., 2005). The number of additional dates required to yield significant improvement in age-model performance depends on a number of factors, including the rate of sediment accumulation, the geological context, lithostratigraphic variability, processes of recruitment of organic debris and preservation factors. Furthermore, radiocarbon time is not linear, and hence distortions caused by variations in atmospheric radiocarbon activity are difficult to evaluate unless the data are calibrated: the true chronological order of a series of dates can only be determined after calibration (Bowman, 1990). In order to achieve centennial to sub-centennial resolution in calibrated age models, however, several tens or perhaps even hundreds of radiocarbon measurements may be required for each dated series (Blaauw et al., 2003; Telford et al., 2004a, b).

3.4. Development of statistical tools for calibration of radiocarbon data-sets

In recent years, a number of statistical approaches have been applied to the analysis of radiocarbon age series. These aid the process of calibrating radiocarbon-based age models and generate more realistic estimates of age uncertainties, by testing for the optimal statistical match between a stratigraphical series of radiocarbon dates and the detailed structure of the calibration model (radiocarbon 'wiggle-matching'). The most widely used have been Bayesian statistical procedures (see Blaauw et al., 2003, 2004; Blockley et al., 2004, 2008; Davies et al., 2004; Wohlfarth et al., 2006; Bronk Ramsey, 2008). Major advantages of these new approaches are that (a) they employ the full radiocarbon inventory generated for a sequence, no data being excluded until analysis is complete; (b) they make explicit any data selection steps employed; (c) they generate an infinite number of iterations of tests of the match between the radiocarbon and calibration data; (d) they treat the probability distribution of individual radiocarbon age measurements independently in the analysis, so that the outcomes are not influenced by pre-judgment on the part of the operator and (e) they employ standardized routines for integrating the complex non-Gaussian probability distributions of the calibrated data. The great advantage of these new procedures is that they provide an objective test of age-model performance that is independent of chrono- and or climatostratigraphic assumptions.

The strategy outlined above is undoubtedly more time-consuming to implement (more extensive laboratory procedures), and is also likely to involve significantly greater expense (the costs of much larger numbers of radiocarbon dates, etc.), and hence is not necessarily being advocated for routine or preliminary investigations where 'rangefinder' age estimates may be adequate for purpose. It is perhaps best reserved for the dating of important regional type-sites or of sequences considered key in other respects, where the aim is to optimise age models with respect to precision and accuracy. In those cases, however, there is a further step that needs to be taken, for the outcomes of the age-modelling exercises must be independently validated if the resulting age estimates are to be used as temporal 'pinning points' in regional stratigraphic schemes and in subsequent time-stratigraphic correlation. This point is addressed in the following section.

4. Validating regional correlations using tephrochronology

There are two principal ways in which radiocarbon-based age models can be validated. The first involves the application of additional dating methods to the radiocarbon-dated sediment sequence, such as U-series dating or varve counting (e.g. Prasad et al., 2004). While this is perhaps the optimum scenario, there are, unfortunately, relatively few sites that offer the potential for multiple dating, and this is particularly the case in the marine realm. An alternative approach exploits discrete time-parallel marker horizons that can be detected in two or more sequences, for example distinct boundaries between palaeomagnetic or oxygen isotope stratigraphic units (e.g. Ising, 2001; von Grafenstein et al., 2004). One type of marker horizon which has been increasingly employed as a basis for correlation in the North Atlantic region is tephra.

Tephra layers of known provenance can provide precise time-lines between records, even when the absolute ages of the tephras are not known (*tephrostratigraphy*). However, they can also provide dates for the horizons in which they occur if their ages have already been established (*tephrochronology*). For many years, tephrochronology was concerned solely with visible tephra horizons that could be observed in open sections or sediment cores (Einarsson, 1986), but rapid progress has since been made in the detection and analysis of non-visible, microscopically fine ash known as '*cryptotephras*' or '*microtephras*' (Turney, 1998; Turney and Lowe, 2001; Wastegård, 2005). Important recent developments include the detection of fine ash layers in Greenland ice cores (Mortensen et al., 2005), a major extension of the geographical ranges over which certain tephras can now be traced (Davies et al., 2003; Turney et al., 2006c; Wastegård et al., 2006; Blockley et al., 2007a, b), and the discovery of new tephras not represented in the visible tephra record (e.g. Davies et al., 2004; Wastegård et al., 2006; Pyne-O'Donnell, 2007). All of these significantly enhance the potential of tephrochronology in the synchronisation of ice-core, marine and terrestrial sequences (Blockley et al., 2008). In addition, fine volcanic ash layers of a few centimetres in thickness have been detected in deep-marine sequences in both the North Atlantic (J.J. Lowe, S. Pyne-O'Donnell et al., unpublished) and the Mediterranean Sea (Lowe et al., 2007). Although these may consist of microscopic glass shards that form delicate thin bands within the sediment column, they can remain intact, unaffected or only weakly disturbed by bioturbation or sediment redeposition. Their number within a single core sequence can often exceed the number of visible tephra layers preserved in the sediments.

Fig. 2 lists the tephra layers of Icelandic origin from the Last Termination in sedimentary records from the North Atlantic region. Most have not yet been dated directly, but an estimate of age can be obtained from their stratigraphic position within the regional climatostratigraphic scheme. Others can be more precisely dated, however, using the approaches summarised in the previous section (e.g. Saksunarvatn Ash—Birks et al., 1996; Gulliksen et al., 1998) or, where they have been detected in the Greenland ice cores, using the established ice-core chronologies (e.g. Saksunarvatn, Vedde and Fugloyarbanki tephras).

Despite the recent advances that have been made in North Atlantic tephrochronology, however, there are two important issues that need to be resolved. First, it has proved particularly difficult to determine the relative order of age of tephras for which radiocarbon dates are very similar, but which have not yet been found in superposition in the same stratigraphic sequence. It has, for example, not been possible to make a temporal distinction between the Penifiler and the Roddans Port tephras, and also to discriminate between several of the tephras that date to the early Holocene. A further difficulty is that some tephras (e.g. Borrobol and Penifiler) have very similar chemical compositions, at least as determined on the basis of major element ratios (e.g. Pyne-O'Donnell et al., 2008). The Katla Volcanic Centre on Iceland, for example, seems to have been episodically active throughout the Lateglacial and early Holocene periods, and has deposited a series of tephras with very similar chemistry. It may be difficult, therefore, to determine which volcanic event is represented in sequences where only one of the layers is represented (Pearce et al., in press).

The above problems notwithstanding, it is clear that tephrostratigraphy and tephrochronology offer considerable potential for synchronizing Last Termination records from around the North Atlantic. Some of the tephras are widely dispersed, most notably the Vedde Ash which has now been detected in lake sites stretching from Ireland in the west to St. Petersburg in the east, and from Norway southwards into Switzerland. It has also been found in a number of marine cores stretching from the western margin of the North Atlantic (J.J. Lowe, S. Pyne-O'Donnell, unpublished) to the Icelandic, Greenland–Iceland–Norwegian, and North Seas. The pace of research on North Atlantic tephras has quickened over the past decade, and new data on the distribution, provenance, chemical composition and age of tephra horizons are emerging each year. Fig. 2 should be regarded, therefore, as no more than a summary of the current (2007) situation and will undoubtedly require revision and update in the near future.

5. Revised INTIMATE protocol for synchronising Last Termination records

In light of the foregoing, the INTIMATE group recommends the following general protocol for the interpretation, synthesis and correlation of records that span the Last Termination:

1. Palaeoenvironmental interpretations should be based on independent and (preferably) quantified proxy data, and site records should be defined using a local stratigraphic terminology. It is especially important that, wherever possible, palaeoclimatic reconstructions are quantified, and the means by which the palaeotemperature/palaeoprecipitation estimates have been obtained are explained.

2. The timing and duration of palaeoenvironmental events should be based on independently generated radiocarbon-based age models. The original (i.e. uncalibrated) radiocarbon dates should always be provided, and any steps taken to discard, adjust or calibrate the age estimates should be explained, and should include detailed reference to the analytical tools employed.
3. It is essential that, in future, radiocarbon dates are obtained only from materials of the highest integrity. This will involve greater care and discrimination in sample selection, and further progress in the refinement and purification of sample material.
4. The palaeonvironmental reconstructions and chronologies that emerge from steps 1 to 3 should then be compared with an independent regional stratotype, and the degree of compatibility with the stratotype sequence assessed, taking account of any dating uncertainties. Henceforth, the North Atlantic INTIMATE group will adopt the NGRIP record as a regional stratotype, with the timing and duration of events defined using the GICC05 chronology.
5. Proposed correlations resulting from step 4 should be validated using independent dating and/or correlation methods. Of these, tephrochronology offers the most effective and immediately applicable basis for validation of radiocarbon chronologies for time-stratigraphic correlation, particularly in the North Atlantic region, but also in other areas such as New Zealand (Alloway et al., 2007). Indeed, there is a realistic prospect that tephrochronology could replace radiocarbon as a more effective dating tool for some North Atlantic and New Zealand records, if tephras can be shown to be widely dispersed, to have diagnostic chemical 'signatures', and ages that can be determined precisely. In certain sites and circumstances, annually laminated sediments in lacustrine and/or marine sequences, or dendrochronological records, will not only provide a basis for validating radiocarbon-based chronologies, but will comprise a record that is superior to radiocarbon in terms of temporal resolution. While the aim must be to employ such sequences whenever possible, it is acknowledged that they are relatively uncommon, and hence the two-pronged approach of radiocarbon and tephrochronology seems likely to form the basis for the synchronisation of Last Termination ice-core, marine and terrestrial proxy-climate records, at least for the foreseeable future.

It is the view of the INTIMATE group that the implementation of this approach, which involves a sensible approach to stratigraphy, dating ingenuity, and optimal use of the NGRIP event stratigraphy and GICC05 chronology, will provide a much clearer picture of the nature, order and timing of events in the North Atlantic region during the Last Termination, which is probably the best accessible palaeoclimatic laboratory on earth for testing competing ideas about the mechanisms of abrupt climatic change. It is therefore commended to the wider Quaternary community.

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Appendix. Members of the North Atlantic INTIMATE group

The following members of the INQUA North Atlantic INTIMATE project attended the 8th International Workshop held in Iceland in September 2005, and contributed to the discussions which led to the revised INTIMATE protocol outlined in this paper.

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