

**Dating, synthesis, and interpretation of palaeoclimatic records of the last glacial cycle and model-data integration: advances of the INTIMATE (INTegration of Ice-core, MARine and TERrestrial records) COST Action ES0907**

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**Abstract**

Since 2010, the INTIMATE (INTegration of Ice-core, MARine and TERrestrial records) network has been operating as a COST Action (designated ES0907). This paper outlines the accomplishments of the INTIMATE COST Action in the context of how the INTIMATE ideas have evolved during the network's twenty-year life

span, and highlights a number of challenges that can guide further work. In the second part of the paper, the contributions that comprise this INTIMATE special issue are introduced.

## 1. Introduction

The publication of this Special Issue of *Quaternary Science Reviews* marks the twentieth anniversary of the INTIMATE (INTEgration of Ice-core, MARine and TERrestrial records) programme, formerly a project and International Focus Group recognized and supported by INQUA. Founded in 1995 at the Berlin INQUA Congress as a successor to the North Atlantic Seaboard Programme of IGCP-253 (Termination of the Pleistocene: Lowe et al. (1994)), the aim of INTIMATE was the integration of proxy climate records from around the North Atlantic region during the last glacial-interglacial transition (Last Termination: (Walker et al., 2001)). Subsequently, the INTIMATE remit has expanded geographically, to include the whole Atlantic basin and also Australasia (Alloway et al., 2007; Turney et al., 2006), while an extended time scale covers the early Holocene and deeper parts of the Late Quaternary record. An initial expansion of the INTIMATE timeframe back to 30 ka (thousand years before present, present referring to A.D. 1950 unless otherwise indicated) (Lowe et al., 2008) was followed by a further extension to 60 ka (Blockley et al., 2012). The latest development, described in papers in this Special Issue, doubles that time range and means that the temporal span of the INTIMATE programme is now the entire last glacial cycle (Rasmussen et al., in this issue). This most recent phase of INTIMATE has been funded through the European COST Action ES0907, and will be described in section 3. Before that, however, we briefly consider the contributions of the INTIMATE community to Late Quaternary climate science in the years up until 2010, when the COST Action began. Further details on the history of INTIMATE and of its predecessor, the North Atlantic Seaboard Programme, can be found on the INTIMATE web page, <http://intimate.nbi.ku.dk/>.

## 2. INTIMATE 1995-2010

It had become apparent during the course of the North Atlantic Seaboard Programme that the chronostratigraphic subdivisions of the Lateglacial that had been employed initially in Scandinavia (Mangerud et al., 1974) and subsequently in other areas of Europe, and which were based on radiocarbon-dated biozones (chronozones), were becoming increasingly difficult to apply in the classification and subdivision of proxy climate records from the Last Termination. Problems of time-transgression in vegetation records, inconsistencies in the use of terms such as Bølling and Allerød ('interstadial', 'biozone', 'chronozone') and uncertainties in radiocarbon dating, arising both from variations in the atmospheric  $^{14}\text{C}/^{12}\text{C}$  ratio and from site-specific or laboratory-specific factors, meant that an alternative chronostratigraphic subdivision of the Last Termination was required. In addition, it was evident that new

bases were needed to underpin correlations between the emerging ice-core archives, terrestrial sequences, and palaeoceanographical records from the North Atlantic region, while refinements to the radiocarbon timescale, involving both calibration and age-modelling, were also urgently required. Here we consider some of the ways in which the INTIMATE programme has addressed these and related issues (Table 1).

#### *An event stratigraphy for the North Atlantic region*

Events may be broadly defined as geologically short-lived occurrences that have left some trace in rock records and hence, in principle, provide a basis for correlating geological sequences. At an early stage in the programme, INTIMATE adopted this approach, and employed climatically-driven inflections in the Greenland GRIP oxygen isotope profile as a basis for an event stratigraphy for the time interval 23-11 ka. The record was divided into stadials (GS-1, GS-2) and interstadials (GI-1, GI-2) and their subdivisions (e.g. GI-1a, 1b, 1c, 1d, 1e). These formed a stratigraphic template for the sequence of climatic changes that occurred during the Last Termination in Greenland and adjacent areas of the North Atlantic region. Introduced in 1998 (Björck et al., 1998; Walker et al., 1999), the Greenland record constitutes a stratotype against which events that are reflected in proxy climate data from other parts of the North Atlantic province can be independently compared. As the timeframe of INTIMATE was extended backwards, the event stratigraphy was extended accordingly: first to 30 ka b2k (Lowe et al., 2008) and subsequently to 48 ka b2k (Blockley et al., 2012), with “b2k” adopted from ice-core age reporting and denoting years before A.D. 2000 .

#### *Protocols for ice-ocean-land correlation*

Over the last fifteen years, INTIMATE has formulated a series of protocols for correlating proxy climate records from ice-core, ocean and terrestrial contexts. These have included:

- i. recommendations for the use of  $^{14}\text{C}$  ages and for the derivation of reliable age estimates based on  $^{14}\text{C}$  (including issues of site selection; the provision of contextual information on  $^{14}\text{C}$  ages; the application of internationally-agreed calibration protocols, such as IntCal; wiggle-matching to the  $^{14}\text{C}$  calibration curve; and the employment of Bayesian and other statistical methods),
- ii. the use of an event-stratigraphic approach (see above) in inter-regional correlations, and
- iii. the employment of time-parallel marker-horizons based on tephra isochrons,  $\delta^{18}\text{O}$  stratigraphy, and palaeomagnetic signals (Lowe et al., 2001; Lowe et al., 2008).

#### *Developments in geochronology*

INTIMATE scientists have been closely involved in four important aspects of the geochronology of the Last Termination:

- i. in the refinement of  $^{14}\text{C}$  age modelling using Bayesian and other statistical approaches (e.g. Blockley et al. (2008a); Blockley et al. (2007); Blockley et al. (2008b); Bronk Ramsey (2008, 2009); Bronk Ramsey et al. (2012))  
in the refinement of the IntCal radiocarbon calibration programme (Reimer et al., 2009; Reimer et al., 2013), particularly in the extension of the dendrochronologically-based section of the calibration curve into the Lateglacial (Friedrich et al., 2004; Kaiser et al., 2012),
- ii. in the development of high-resolution ice-core chronologies, most notably the composite GICC05 timescale based on three separate ice cores and which now underpins the INTIMATE event stratigraphy (Andersen et al., 2006; Rasmussen et al., 2006; Rasmussen et al., in this issue; Rasmussen et al., 2008; Svensson et al., 2008; Vinther et al., 2007), and
- iii. in the development of high-resolution Lateglacial varve stratigraphies (Brauer et al., 1999).

#### *Developments in tephrochronology*

Major advances have been made in the tephrostratigraphy of the Last Termination in the North Atlantic region. They include the recovery of non-visible tephras from marine and terrestrial sediments (cryptotephra); refinements in the geochemical fingerprinting of tephras; the dating of tephra horizons; the detection of volcanic signals and tephra shards in ice cores; the extension of the geographical ranges of the dispersal 'footprints' of tephras; and the construction of comprehensive regional tephra data-bases. In the North Atlantic region, for example, more than twenty discrete tephra isochrones have been identified from the Last Termination alone. INTIMATE scientists have been at the forefront of many of these developments (Blockley et al., 2008a; Blockley et al., 2012; Davies et al., 2012; Davies et al., 2002; Davies et al., 2010).

#### *The Greenland ice-core record*

Over the past twenty years, members of the INTIMATE group have been closely involved in drilling to bedrock near the thickest part of the Greenland ice sheet, notably the international ice-core projects GRIP, NGRIP, and NEEM. The data have provided startling evidence not only of the amplitude of climate change over the last interglacial-glacial cycle, but also of the rapidity of those changes with, in many instances, temperatures shifting by more than  $10^{\circ}\text{C}$  within decades (Johnsen et al., 1992; Kindler et al., 2014; NEEM community members, 2013; North Greenland Ice Core Project members, 2004; Steffensen et al., 2008). These discoveries have led to a major re-evaluation of the pattern, sequence, and timing of climatic events during the last glacial cycle in the North Atlantic region.

#### *Ratification of the Pleistocene-Holocene boundary*

In 2004, a Joint Working Group of INTIMATE and the Subcommittee on Quaternary Stratigraphy (SQS) was

established to bring forward a proposal for the definition of the Pleistocene-Holocene boundary (Global Boundary Stratotype Section and Point: GSSP). The boundary was identified at 1492.45 m depth in the NorthGRIP Greenland ice-core based on a range of physical and chemical properties with an age estimate obtained from the annual layer-counted GICC05 timescale (Walker et al., 2008). Five auxiliary stratotypes (Splan Pond, eastern Canada; Cariaco Basin, Venezuela; Eifelmaar Lakes, Germany; Lake Suigetsu, Japan; and Lake Maratoto, New Zealand) were also recommended (Walker et al., 2009). The Pleistocene-Holocene boundary GSSP was ratified by the International Union of Geological Sciences (IUGS) in May 2008. As a result, the Holocene is now formally constituted as a unit of Series/Epoch rank within the International Geological Time Scale (Cohen et al., 2013).

### *Overview*

While the INTIMATE community has made a significant contribution in a number of different areas to our understanding of the operation of the ocean-cryosphere-atmosphere systems over the course of the last glacial cycle, and especially during the Last Termination, four inter-related themes characterised INTIMATE-related research in the first fifteen years of the programme. These were (i) the development of the Greenland event stratigraphy for ordering and naming climatic events, and as the stratotype for the North Atlantic region; (ii) the refinement of age models based principally on radiocarbon dating; (iii) the use of tephrochronology as a basis for correlating proxy climate records from a range of different depositional contexts; and (iv) the analysis, at a range of spatial scales, of abrupt climatic events and their possible causes and likely effects (Brauer et al., 2008; Hoek et al., 2008).

The key component of the INTIMATE programme has been the event stratigraphy and, while in its initial manifestation, it was affected by dating uncertainties associated with the modelled ice-core time scales beyond 14.5 ka (Johnsen et al., 2001), the development of the annual-layer counted GICC05 time scale which extended throughout the INTIMATE time range, placed the scheme on a much more secure chronological footing (Lowe et al., 2008). At the same time, the refinement of radiocarbon age models employing the latest iterations of the IntCal calibrations (IntCal98, IntCal04 and IntCal09), coupled with the increasing use of probabilistic assessments of age-depth data using Bayesian-based techniques (Bronk Ramsey, 2009), enabled increasingly secure radiocarbon-based age estimates to be obtained from limnic and other contexts (e.g. Lohne et al., 2013, 2014). In addition, a greater understanding of the marine reservoir effect – and its spatial and temporal variations – meant more reliable corrections could be made to radiocarbon ages derived from, for example, marine foraminifera and mollusca (Björck et al., 2003; Cage et al., 2008; Reimer et al., 2009). Equally significant have been the advances in tephrochronology, notably

the detection of volcanic signals in the ice cores that can be related to tephra isochrones recorded in the marine and terrestrial realms; the extension of the Icelandic tephra network eastwards across Europe; and the linking of the north European tephra framework with tephras from the Mediterranean volcanic province (Davies et al., 2012; Davies et al., 2010; Lane et al., 2011).

These three developments clearly have important implications for the fourth of the themes outlined above, namely the recognition in different sedimentary contexts of evidence for abrupt climatic events and, in particular, the dating and correlation of these events. A leitmotif of the INTIMATE programme has been to test whether clearly identifiable climatic events are synchronous or time transgressive and, if the latter, how far is it possible to calibrate the environmental response to climate change. In other words, are we yet in a position to detect leads and lags in the climate system? There is no doubt that significant steps towards these goals were made during the early and middle years of the INTIMATE programme, but it is maybe only within the last four years that some of these endeavours have come to fruition. It is to these aspects of INTIMATE that we now turn our attention.

### **3. The INTIMATE COST Action 2010-2014**

Following the INTIMATE workshop in Oxford in 2008, the newly-elected INTIMATE Chair, Chris Turney, led an application for future funding through the EU COST (European Cooperation in Science and Technology) Action Programme. This was successful and the new INTIMATE COST Action (designated ES0907) was formally inaugurated with a Management Committee (MC) meeting in Brussels on June 26<sup>th</sup>, 2010. Chris Turney was elected chairman of the Action and working group leaders were appointed. Work on the programme began in 2011 after Sune O. Rasmussen took over the chairmanship of COST-INTIMATE following Chris Turney's departure to take up an Australian Research Council Laureate Fellowship at the University of New South Wales.

The generous funding allocated from the COST budget has made possible a significant expansion of INTIMATE's activities in relation to the topics covered, the number and size of supported collaborative events, and the institutional and geographical spread of participants. A new approach within the INTIMATE COST work plan has been the inclusion of a palaeoclimate modelling dimension, with a series of initiatives designed to develop and encourage closer collaboration between palaeoclimate modellers and scientists generating empirical (proxy) data. Under the COST structure, INTIMATE was able to broaden its geographical base, and now has a strong representation of scientists based in Southwest, Central, and East

Europe, resulting in a significant expansion of the INTIMATE study area. An important component of the COST initiative has been the involvement of young scientists, with about 40% of all workshop and meeting participants having been Early Stage Researchers (defined within COST as researchers with up to 8 years of experience after completion of a PhD degree). Over the three and a half years of its operation, the COST Action has supported four large open workshops (with integrated MC meetings), a number of topic-specific collaborative workshops, summer training schools, and a thriving research exchange programme (comprising Short Term Scientific Missions: STSMs, in COST terms). Detailed reports from all meetings, workshops, and STSMs are available from the INTIMATE COST Action web page <http://cost-es0907.geoenvi.org/>. Here we outline the principal results from the four constituent working groups.

#### *Working Group 1: Dating and Chronological Modelling*

The main prerequisites for meaningful climate reconstructions from sedimentary records are robust chronological frameworks. In particular, the identification of decadal- to centennial-scale leads and lags in regional climate changes and/or of proxy responses needs very precise correlation between independent palaeoclimatic records without recourse to event alignment, as the latter assumes, rather than tests for, synchronous climatic behaviour (see e.g. Blaauw, 2012). Working group 1 (WG1) focused on developing the tools and methods that would deliver age models with improved precision for records that fall within the INTIMATE period of 60 – 8 ka. The main challenge was the standardisation of age models using dating methods based on fundamentally different principles (e.g. layer counting or radiometric methods) from a wide variety of geological records (e.g. ice cores, lake and marine sediments, speleothems, geomorphological evidence). A significant outcome is the protocol presented by Brauer et al. (in this issue), in which the transparent reporting of both age estimates and uncertainties is a key element. In order to reduce the ranges of uncertainty associated with age models, emphasis has been placed on the routine employment of isochrons (age-equivalent markers, such as tephra layers and palaeomagnetic signals) to provide independent tests of the models.

WG1 scientists have also been actively involved in the international effort aimed at improving the precision of the radiocarbon calibration curve beyond the limits of the tree-ring-based time scale (Hajdas, 2014; Muscheler et al., 2014). The recent iteration of the international calibration programme, IntCal13 (Reimer et al., 2013), is, in part, based on  $^{14}\text{C}$  dating of macrofossils (Bronk Ramsey et al., 2012) and varve counting (Schlollaut et al., 2012) within the frame of the Suigetsu Project (Nakagawa et al., 2012), to which members of COST-INTIMATE have contributed.

A significant advance within the remit of WG1 has been in tephrochronology, notably in the development of tephrochronological frameworks that enable high-precision correlation between different sedimentary sequences. Over the duration of the COST Action, for example, a number of new tephra layers have been detected within Greenland ice-core archives (e.g. Abbott and Davies, 2012; Davies et al., 2010), while the recent discovery of Icelandic tephra south of the Alps has enabled the INTIMATE tephra lattice to be extended into Southern Europe (Lane et al., 2011) and into the Mediterranean Sea (e.g. Bourne et al., 2010). These developments are reviewed in two papers in this issue (Blockley et al., in this issue; Davies et al., in this issue). Tephrochronological correlation of independently-dated lacustrine records (based on radiometric and varve counting) has also enabled regional-scale climatic changes to be quantified in time and space, and leads and lags in the climate system to be identified as, for example, during the Younger Dryas in northern Europe (Lane et al., 2013). In addition, tephra-based correlations have enabled temporal offsets to be determined between independently-derived timescales. For example, comparison between the Greenland ice-core record and the lacustrine sequence from Kråkenes, western Norway, using the Vedde and Saksunarvatn ashes, showed that the GICC05 Greenland ice-core time scale is 57-87 year older than the Bayesian-based radiocarbon age model for Kråkenes during the time period 12 – 10 ka b2k (Lohne et al., 2013, 2014). This accords with a time scale offset of 70 years established independently by Muscheler et al. (in this issue) through synchronization of tree-ring  $^{14}\text{C}$  and ice-core  $^{10}\text{Be}$  records.

In collaboration with the INQUA-funded project ACER (Abrupt Climate Changes and Environmental Responses) which has cognate scientific objectives, a protocol has been developed for archiving records and their associated chronologies on a common database. This includes both new and previously-published (but revised) records (Sanchez Goñi and Harrison, 2010, and further work in preparation). ACER and INTIMATE have also collaborated in the development of an expanded database for marine reservoir age corrections as part of a long-standing international project building on the existing database of (Reimer and Reimer, 2001).

Finally, WG1 members have been exploring improved age modelling techniques for integrating radiocarbon-based chronologies with other data, such as tephra-based age estimates and correlations, using new bespoke software developed within the INTIMATE programme as described in Bronk Ramsey et al. (in this issue). During the COST-INTIMATE workshops held in Oxford in 2012 and Blair Atholl, Scotland, in 2013, Bayesian statistical tools for age modelling were tested against a range of site records and new integration software for multiple palaeoclimate records was also trialled using data generated by members of WG1. This database and the associated chronology transfer and presentation tools are integral to the



future work of the INTIMATE network, but they will also be valuable to the wider Quaternary community, and will be openly accessible at <https://c14.arch.ox.ac.uk/intimate/db.php>.

*Working Group 2: Quantification of Past Climate.*

Working group 2 (WG2) has focused on obtaining quantitative climatic data (e.g. palaeotemperature and palaeoprecipitation estimates) from North Atlantic and European sequences, including marine and terrestrial records. Efforts were directed towards the integration of different archives as a way to understand the processes and feedbacks active in the climate system. Under the auspices of WG2, several data compilation efforts have been undertaken that allow comparison of reconstructions of past climate and environmental change in the time interval 60 – 8 ka. Three comprehensive data syntheses have resulted from the compilation of terrestrial sequences from Western European (Moreno et al., in this issue), Central and Eastern European (Feurdean et al., in this issue) and the Alpine region (Heiri et al., in this issue). In total these compilations comprise more than a hundred terrestrial records that are now available to the scientific community in a standardized format, including lake and peat records, speleothems, loess-paleosol sequences and glacier deposits. This represents a major step forward for the European terrestrial community, making standardised data available electronically to a much broader audience. In addition, several deep-sea records have been compiled enabling sea-surface temperature and ice-rafted debris variability in the North Atlantic to be reconstructed (Antje Voelker, pers. comm.).

In the work of WG2, and in particular during the data syntheses, special attention was directed towards the standardization of tools and methods used to quantify past changes and to the techniques employed to obtain quantitative data (supplementary information of Moreno et al., in this issue). In addition, the main sources of uncertainty in the different proxy types and in the different archives of climate variability were interrogated. The available compilations allowed the group to obtain a detailed overview of continental climate during the last deglaciation and to determine climate gradients along a latitudinal transect. Most of the existing Western European palaeoclimate records that provide quantitative climate information are constrained to a relatively narrow latitudinal band from 53 to 45°N. Records from Scandinavia and the Mediterranean will therefore be of particular interest for future comparable investigations within the terrestrial palaeoclimate community. In general, the number of high-resolution palaeoclimate records that extend beyond the Last Glacial Maximum is very limited, and it has not been possible to reconstruct millennial-scale climate variability over this period from terrestrial archives. Despite progress during the COST Action and the work undertaken within WG1, a key conclusion of the compilation efforts is that more work is needed to merge terrestrial with marine records using a common chronological

framework. Furthermore, an urgent need to increase the number of regional training sets that support quantitative climate reconstruction based on, for example, chironomid, pollen, and diatom data, was clearly identified.

### *Working Group 3: Modelling Mechanisms of Past Change.*

Activities of working group 3 (WG3) have been focused on integrating data and models in a consistent framework using both equilibrium and transient simulations. One recent example supported by the INTIMATE COST Action is the integration of data with equilibrium experiments for successful validation of simulated late-glacial temperatures in Europe using a consistent, standardized chironomid-based palaeotemperature data-set (Heiri et al., 2014). The use of transient simulations over relatively long time periods with three-dimensional coupled climate models is a relatively new development. One period that has attracted particular interest among the modelling community is the last deglaciation, from ca. 21 ka to the Holocene. The joint influence of large changes in greenhouse gas concentrations (Monnin et al., 2001), ice-sheet changes (e.g., Peltier, 2004) and orbital evolution (Berger, 1978) produced drastic climate changes that are recorded in many archives. It is thus a natural target for evaluation of the performance of climate models.

Within INTIMATE, a set of deglaciation experiments (Bethke et al., 2012; Kahana and Valdes, 2009; Liu et al., 2012; Liu et al., 2009; Roche et al., 2011) has been evaluated with two particular questions in mind: (i) are simulations with slow forcing only (*i.e.* excluding rapid freshwater fluxes) consistent across different coupled climate models, and (ii) when rapid freshwater forcing is included, what is the best experimental scenario to use when including it in the simulations? Extended discussions during two workshops led to the conclusions that the three different climate models by Kahana and Valdes (2009), Roche et al. (2011), and Bethke et al. (2012) seem to reproduce a similar deglaciation history when forced by orbital evolution, greenhouse gases and imposed ice-sheet evolution, a history that is broadly consistent with empirically based records for the northern hemisphere (in particular the Greenland ice-core records when interpreted in terms of temperature evolution). However, different climate models forced with the same freshwater history, e.g. those reported by Kahana and Valdes (2009) and Bethke et al. (2012), do not yield the same result due to their very different AMOC sensitivities to freshwater influx. On a related note, there is no consensus on the degree to which deglacial freshwater history is likely to be in better accordance with data, and different groups are using very different philosophies when creating a freshwater forcing scenario. For example, Liu et al. (2012) based their scenario on the climatic effect generated by their model, while Bethke et al. (2012) used a time-derivative of sea-level data. Putting all these observations together,

WG3 formulated two recommendations for freshwater perturbation experiments of the last deglaciation. The first of these recommends the use of a freshwater scenario that, once integrated in time and space over the last deglaciation, is consistent with the known sea-level evolution (e.g., Peltier and Fairbanks, 2006) and the broadly known evolution of the ice-sheet complex over this period (Peltier, 2004). An example of such a method is given in Bethke et al. (2012). The second recommendation is to analyse the model response to freshwater fluxes in different geographical zones and for different flux magnitudes to better understand the nature of the responses of individual models (Kageyama et al., 2010; Roche et al., 2007b; Stouffer et al., 2006), and to repeat this for different climate settings (Van Meerbeeck et al., 2011). These recommendations have now been integrated into a new transient deglaciation modelling working group of the Palaeoclimate Model Intercomparison Project (PMIP3). This will allow a more thorough analysis of the robustness of the results using a much larger range of models.

Several simulations with forward modelling of water isotopes have been either specifically performed within INTIMATE (cf. Roche et al., in this issue) or presented and discussed within the INTIMATE group (Caley et al., 2014; Sjolte et al., 2011). A focused workshop evaluated one simulation of the last deglaciation that included water-isotope data from the different realms. Issues pertaining to the representative scale of the proxy measured, both in time (seasonal, annual, etc.) and space (regional or local) and its representation in climate models were reviewed. Two of these are expected to lead to further community manuscripts: the first on the compilation of data from all possible realms across a stadial period containing a Heinrich Event (often denoted 'a Heinrich Stadial', (Rasmussen et al., in this issue)) as a target for the modelling community, and the second is a recommendation of best practice when using model – data comparisons with water isotopes. Two main drawbacks of model simulations presented during the WG3 proceedings were identified. First, the model results lack abrupt events similar to those represented in most northern Atlantic archives, since coupled climate models do not generally spontaneously produce abrupt millennial-scale events unless forced using freshwater perturbations. Second, the resolution of the climate models is generally low, while empirical data-sets usually represent very local site-specific information. For example, high-resolution topography is needed for modelling the response of Alpine speleothems to changing climate. Overall, the comparison of simulated water isotopes with observations was promising and follow-up studies were commissioned to analyse further the potential of using water isotopes within downscaling methods to approach the spatial resolution issue.

Some progress has also been made on carbon-cycle modelling within coupled transient simulations. These are expected to improve the correlation of sediment cores between different oceanic regions through

simulation of the  $^{14}\text{C}$  reservoir ages (Mariotti et al., 2013) and to advance understanding of the link between AMOC and  $\delta^{13}\text{C}$  in the ocean.

Finally, close cooperation between WG3 group and other groups within the COST action have fostered fruitful advances. In particular, excellent progress has been made in quantitative model – data integration using objective methods, as presented for the oceanic realm in Roche et al. (in this issue) and in the validation of climate model-inferred regional temperature change with, particularly, chironomid-based palaeotemperature reconstructions (Heiri et al., in this issue).

#### *Working Group 4: Climate Impacts.*

Within the temporal range considered by the COST Action (60 – 8 ka), climate conditions ranged from full glacial to interglacial conditions, including a series of millennial-scale stadial and interstadial and shorter-lived (decadal-centennial) events (see Rasmussen et al., in this issue). Working group 4 (WG4) has been focusing on the impact of these climate events of different duration and amplitude on ecosystems as reflected in palaeoenvironmental records. Workshops dedicated to WG4 include a workshop on integrating palaeoenvironmental and archaeological data sets (Ghent, Belgium, 2012), a joint WG2-WG4 workshop on terrestrial records from Eastern Europe (Cluj-Napoca, Romania, 2013) and a workshop on climate impacts on sedimentary environments (Utrecht, The Netherlands, 2013). The results of the different workshops are presently being compiled for two special issues of Quaternary International led by Wim Hoek et al., and Aurel Perşoiu et al., while other contributions are presented in this volume (Feurdean et al., in this issue). Important new results are directly linked to the enlargement of the network by, for instance, including archaeological records (Birks et al., in press). During workshops and symposium sessions, several data inventories have been made to reveal the nature and quality of climate reconstructions of past environmental change across the full range of European environments (Mediterranean to sub-Arctic). The majority of the data available consists of palynological records from lakes or peat-bogs covering the period 15 – 8 ka. Records from full Glacial (GS-2) and older interstadial periods are relatively scarce. During the work with the data inventories, it was apparent that only a few of the interstadials are clearly represented in terrestrial records, namely GI-1, GI-4, GI-8, and GI-12 (Hoek et al., pers. comm.). This is partly related to poor preservation of these older deposits and occurrence of these deposits at greater depth, usually not reached by manual coring. However, climate conditions during relatively cold periods like GS-2 were also less favourable for the development of vegetation and formation of organic deposits containing botanical and (micro-)faunal remains, particularly in Northern Europe. Archaeological, (macro-)faunal assemblage, and geomorphological records are generally discontinuous through time, but they can give some valuable

information on the environmental conditions that prevailed during colder phases of the period under investigation.

Because most records represent local conditions, the impact of climate on an ecosystem can only be assessed when the environment in which the record developed is understood. The investigation of multiple proxies and information about the environmental setting of the basin of deposition are crucial and this has been the approach advocated by the INTIMATE group. Notably, it has been applied in the 'INTIMATE example' projects, where multi-parameter investigations were undertaken by students and more experienced researchers during two field-based summer schools in Hämelsee (Germany, summer 2013) and Lake St. Anne (Romania, summer 2014) (see the COST INTIMATE web page for full accounts of the activities). When independent proxies for climate change are examined in the same stratigraphic levels, a direct comparison between climate and vegetation can be made, as illustrated by studies from all over Europe (Blaga et al., 2013; Muñoz Sobrino et al., 2013; Samartin et al., 2012). Large data-sets from individually dated events from small regions can be assembled in order to build regional chronologies and study the spatial distribution of climate impacts (Hoek, 2001). The compilation of late-glacial chironomid-inferred temperature records and past vegetation across northwest Europe has revealed climate gradients involving both temperature and precipitation (Birks and Birks, in this issue).

Alternatively, detailed correlations using tephrochronology and/or oxygen isotope correlation can make direct correlations to the Greenland ice-core records (Ammann et al., 2013; Lotter et al., 2012; van Asch et al., 2012). The use of the Saksunarvatn and Vedde tephras by Lohne et al. (2013) not only led to the quantification of a time-scale offset between ice-core and radiocarbon ages as discussed above. When relating biotic change over the Allerød – Younger Dryas and the Younger Dryas – Holocene transitions with the Greenland ice-core records and accounting for the time-scale offset, the abrupt transitions as defined by the Greenland ice-core Deuterium-excess signal (Steffensen et al., 2008) preceded the Kråkenes Younger Dryas boundaries by about 30 years. Further evidence for delayed environmental responses compared to the Greenland Deuterium-excess signal has been demonstrated by a recent biomarker isotope study from the Lake Meerfelder Maar sediment record (Rach et al., 2014).

Rates of change of late-glacial ecosystems have been estimated by Birks and Ammann (2000). Birks and Birks (2013) used the Kråkenes <sup>14</sup>C chronology to match timing and rates of independent chironomid-inferred summer temperature changes with vegetation responses shown by macrofossils and pollen at Kråkenes. This approach was extended across northwest Europe by Birks and Birks (in this issue).

Drivers of change include climate (mainly temperature and precipitation), disease, disturbance, and community dynamics. Responses can be direct; for example, where temperature limits of species were exceeded they went locally extinct and where temperature limits became favourable, species expanded. Other responses can be indirect, involving ecosystem processes such as competition, succession, resilience, and immigration. After the immediate responses, long-lasting changes can be initiated, such as immigration and succession, for example in the early Holocene (Birks et al., in press).

As climate varies in space, some ecosystems will be sensitive to change whereas others will be resilient and show no response. Birks et al. (2012) and Birks (in press) documented a major late-glacial climatic discontinuity between southwest and north Norway, between Kråkenes (62°N) and Andøya on Vesterålen archipelago (69°N). In southern Scandinavia the impact of the Younger Dryas cooling was immediate and large. In northern Norway, Allerød and early Younger Dryas summer temperatures were similar and the major factor controlling vegetation development was aridity that increased in the mid-Younger Dryas. Birks et al. (2012) and Birks (in press) demonstrated that tree birch immigrated some 650 years after the start of the Holocene at Kråkenes, after 1000 years on Andøya, and after 1500 years in the far north, whereas the Holocene thermal maximum seems to have been earlier in the north than in south Scandinavia.

#### **4 Overview of papers in this issue**

The papers in this Special Issue of Quaternary Science Reviews reflect the objectives of the four Working Groups of the EU-funded COST INTIMATE programme described above. They also develop a number of themes that were discussed in papers in the previous INTIMATE Special Issue (vol. 36, p. 1-222, 2012). Two linked keynote papers introduce the volume. **Rasmussen et al. (in this issue)** and **Seierstad et al. (in this issue)** present a recent synchronisation of the Greenland NGRIP, GRIP and GISP2 ice cores and analyse the records that are now available on a common time scale. The paper by Seierstad et al. (in this issue) provides details on the synchronisation of the three independent ice-core records, including the alignment of volcanic signals and chemical impurity profiles. While the temperature proxy records from NGRIP, GRIP and GISP2 are generally very similar, the synchronised records reveal differences between Summit (GRIP and GISP2) and NGRIP that reflect changes in precipitation patterns and source areas, and a suggested imprint of Heinrich events in the ice-core records. The paper by Rasmussen et al. (in this issue) uses the parallel records to update and extend the Greenland GS/GI stratigraphic sequence throughout the entire last glacial period providing a key template for comparison and correlation of both regional and hemispherical-scale proxy records during the period of 120 – 8 ka b2k.

The importance of developing secure dating frameworks for proxy climate records (the remit of Working Group 1: *Dating and Chronological Modelling*) is reflected in the fact that more than half of the papers in this Special Issue address issues relating to chronology. In the first of these, **Brauer et al. (in this issue)** provide a concise overview of the principal dating techniques that are routinely applied to records from the last 60 ka, including four radiometric methods (radiocarbon, uranium-series, luminescence, cosmogenic nuclides), and two incremental methods based on layer counting (ice layers, varves). The paper also considers age-modelling and ways in which records can be correlated using age-equivalence approaches, including tephrochronology, and cosmogenic  $^{10}\text{Be}$  and palaeomagnetic variations. **Bronk Ramsey et al. (in this issue)** then discuss uncertainties inherent in correlations between different proxy records, and describe a new database with integral functions that facilitates age-depth modelling and time-scale transformations. This allows users to examine data on any time scale that can be related to the data of interest, as opposed to specifying the use of a particular time scale (or time scales). An ongoing problem in the geochronology of the INTIMATE time frame has been the linking of the radiocarbon and ice-core chronologies. This issue is addressed by **Muscheler et al. (in this issue)** who discuss discrepancies between the GICC05 ice-core and IntCal13 (tree-ring) time scales. They suggest that the cosmic-ray-induced changes in tree ring  $^{14}\text{C}$  and ice-core  $^{10}\text{Be}$  records provides a potential basis for a direct and independent comparison between the two archives, and proposes a time-scale transfer function to compare  $^{14}\text{C}$ -dated and ice-core records on the same time scale.

The use of tephrochronology as a basis for linking ice-core, marine and terrestrial records is reflected in the next group of papers from Working Group 1. The first contribution by **Blockley et al. (in this issue)** presents an updated and extended INTIMATE event stratigraphy based on the NGRIP template, which includes the key tephra horizons that can be used for correlation across Europe, Greenland and the North Atlantic. In a companion paper, **Davies et al. (in this issue)** show how recent tephra discoveries from the earlier part of this time range (130 – 60 ka b2k) in the NGRIP ice core (23 tephtras) and a marine core (20 tephtras) from the Icelandic Basin can be used to construct the first tephrostratigraphical framework for this time interval. This work demonstrates the considerable potential of tephrochronology in providing key tie-points for correlation at the hemispherical scale but, along with the Blockley et al. (in this issue) contribution, it also highlights some of the challenges that are posed for tephrochronology in terms of robust geochemical fingerprinting and a deeper understanding of tephra depositional processes.

Two tephra case studies from the marine realm follow. **Griggs et al. (in this issue)** discuss three marine tephra horizons, Faroe Marine Ash Zones (FMAZ) II, III and IV (50 – 26 ka) in a core from the

southeastern Norwegian Sea. Detailed analysis of geochemical, sedimentological, and shard concentration data shows that FMAZ II and IV are well-resolved primary deposits (as opposed to secondary depositional features) that can be used as isochrons for high-precision correlation. Protocols for optimising the application of tephrochronology to meet the INTIMATE synchronisation goals are set out in the paper. FMAZ II and III, along with North Atlantic Ash Zone (NAAZ) II, are also recorded in a long core raised from the northwestern Icelandic margin, that spans the past 86 ka, described by **Voelker et al. (in this issue)**. In all, 193 tephras are recorded in the core, the majority of which (155) are of Icelandic origin. The greatest tephra concentrations are in the intervals 29 – 24.6 ka (~ GS-3 to GI-4), 40.5 – 36.6 ka (~ GI-8 to GS-10) and 53.8 – 48.5 ka (~ GI-14 to GI-15.2). Several of these tephras have a unique geochemical character and may constitute new chronostratigraphic markers for the North Atlantic region.

Two further contributions from Working Group 1 describe the use of other dating methods. **Újvári et al. (in this issue)** present AMS<sup>14</sup>C and OSL/IRSL ages from a loess-palaeosol sequence in the Carpathian Basin, Hungary, that spans the past 130 ka. AMS<sup>14</sup>C ages on different mollusca species and on charcoals show age ranges that are significantly narrower than those obtained using OSL/IRSL methods. Moreover, the close agreement between AMS<sup>14</sup>C ages on shells of specific loess molluscs and charcoals suggest that this combination of dating media may provide more precise chronologies for loess deposits of the last 40 ka than OSL/IRSL. A different approach to the dating of the more recent part of the INTIMATE time range is provided by **Lougheed et al. (in this issue)**, who employ palaeomagnetic secular variations (PSV) recorded in sediment cores from Fennoscandia. Most PSV studies of sediments are limited to the Holocene epoch but, in this study, data from sites in southern Sweden and northwest Russia enables the existing PSV master curve for Fennoscandia (Fennostack) to be extended back from 11 to 14 ka. This provides a potentially valuable alternative dating tool for the deglacial time interval where sediments are often unsuitable for radiocarbon dating.

The papers from Working Group 2 (*Quantification of Climate*) begin with a compilation by **Moreno et al. (in this issue)** of western European terrestrial records for the time interval 60 – 8 ka. The dataset includes lake records, speleothems, ice cores, and terrestrial proxies in marine sequences, and is restricted to those of high-temporal resolution and/or those that include climate proxies or quantitative reconstructions of environmental parameters, such as temperature and precipitation. The purpose is to provide the palaeo-community with a database of high-quality terrestrial records that will not only facilitate model-data comparisons, but will also identify key areas for future investigations. In a second contribution, **Heiri et al. (in this issue)** examine the same time interval (60 – 8 ka) in the Austrian and Swiss



Alps, and review quantitative and semi-quantitative approaches to the reconstruction of climatic variables. Again, they include in their overview data obtained from a range of proxy records, such as fossil assemblages of biota including chironomids, cladocerans, coleoptera, diatoms, and pollen from peat and lake sediments; oxygen isotope records from speleothems and lake sediments; past variations in tree-line altitudes and glacier equilibrium line altitudes; variations in glacier extent; and loess-palaeosol records. These data provide the basis for both downscaled climate model runs and for forward modelling approaches for quantitative assessments of former climatic conditions. From further east, **Feurdean et al. (in this issue)** present the first detailed synthesis of high-quality climatic and vegetation records from central and eastern Europe. Speleothems and loess records are the principal sources of proxy climate data for the 60 – 20 ka time interval, while pollen records constitute the main data source for the Lateglacial and Holocene. Again, these data are a key resource for climate modelling and for data-model inter-comparison studies. Finally, **Eldevik et al. (in this issue)** provide a comprehensive overview of the climate history of the northern seas (the northern North Atlantic, the Nordic Seas and the Arctic Ocean) from the Last Glacial Maximum to the present day. This shows how regional climate is related to the extent and strength of North Atlantic thermohaline circulation and the Norwegian Atlantic current. The paper includes a detailed temperature record for Norway and the Norwegian Sea, obtained from a synthesis of terrestrial and marine palaeoclimatic reconstructions into a continuous time series. A combination of instrumental records and forward modelling enables this record to be continued through the present and into the future.

The modelling component in the Eldevik et al. (in this issue) paper links Working Group 2 and Working Group 3 (*Modelling Mechanisms of Past Climate*). The principal output from the latter is the contribution by **Roche et al. (in this issue)** who discuss the freshwater and iceberg fluxes into the North Atlantic during Heinrich events and their potential impact on the Atlantic Meridional Overturning Circulation (AMOC). They describe the use of a fully coupled, water-isotope enabled, climate model (iLOVCLIM) to conduct a series of freshwater hosing experiments to evaluate whether LGM freshwater hosing is a good proxy for Heinrich event 1, and whether, by using different freshwater inputs, it is possible to determine the magnitude of AMOC reduction that is most consistent with proxy data records.

Four papers stem from Working Group 4 (Climate impacts). In the first of these, **Birks and Birks (in this issue)** consider the extent to which changes in summer (July) temperature influenced the patterns of vegetation in northwest Europe during the Lateglacial period. The analysis employs chironomid-inferred July air temperature estimates and pollen percentage data from 15 sites extending from western Ireland to northern Germany, and from northern Norway to northwest Spain. The evidence indicates that at the sub-

continental scale, July temperature alone is not a reliable predictor of vegetation patterns during the Lateglacial, and that these are more readily explained in terms of the interaction between temperature and precipitation, combined with other ecological processes, including plant immigration, succession, soil development, and grazing pressures. The second contribution by **Magyari et al. (in this issue)** discusses vegetation response to climate forcing during the Last Glacial Maximum (LGM) and subsequent deglacial period based on the record from Lake St. Ana in the Carpathian Mountains of Romania. In this region, a significant ecological factor during the LGM was extensive biomass burning, reflecting extreme continentality and relatively warm and dry summers. The pollen record suggests an unusual floristic richness and the presence of some temperate deciduous trees during the LGM. The paper also includes a biome reconstruction that can be used by the modelling community to compare model-based hindcasts with palaeo-data.

Two papers from the marine realm complete this Special Issue, both from the mid/low latitude regions of the eastern Atlantic. Using data from a core raised off Mauretania, northwest Africa, **McKay et al. (in this issue)** present a high-resolution, multi-proxy study of the relationships between pelagic and benthic environments over the last 35 ka. These reflect a combination of high latitude cold events and changes in atmospheric and oceanographic dynamics which influence upwelling intensity. Major community shifts in the benthic foraminiferal record that correspond to climatic events occur during late MIS3 (35 – 28 ka), from 28 to 19 ka (Heinrich event 2 and the LGM), Heinrich event 1 and the Bølling-Allerød, Younger Dryas (18 – 11.5 ka) and during the Holocene. In the final contribution, **Salgueiro et al. (in this issue)** use data from fifteen cores taken along the western Iberian margin to reconstruct time-slice maps of spatial and temporal variations in sea-surface temperatures (SSTs) and productivity for specific intervals over the past 35 ka: the LGM, Heinrich Stadials (1, 2a, 2b, 3), the Younger Dryas, and the Holocene (recent and last 8 ka). The LGM was slightly less warm, but more productive relative to the Holocene, while a substantial cooling and decline in productivity is recorded during Heinrich events, reflecting the southward penetration of iceberg-derived melt-water. SSTs during the Holocene show the same latitudinal gradient as at present, with cold but productive areas reflecting coastal upwelling centres.

The publication of this set of papers in *Quaternary Science Reviews*, complemented by the two special issues of *Quaternary International* that are in preparation, brings to a close the COST phase of the INTIMATE programme. It is testimony to the contributions made by scientists from a range of disciplines who have participated in the various workshops and symposia held over the past four years, and whose own research has benefitted from the opportunity to interact and network with colleagues from different countries and with different interests under the INTIMATE umbrella. But INTIMATE has also moved the

science forward. We now know so much more about the operation of, and interactions between, elements of the climate system over the course of the Last Termination and back into the last glacial. Significant advances have been made, for example, in chronology, in correlation, in data-model comparisons, and in the ability to detect leads and lags between climate change and environmental response as reflected in proxy records. But as is always the case in science, there are key questions that remain, and it will be in the next stage of the INTIMATE programme that some of these will be addressed.

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## **Table 1**

Selected milestones in the development of the INTIMATE event stratigraphy and of the scientific framework on which it is based.

Year	<sup>14</sup> C calibration	Continuous tree-ring chronology	Ice core stratigraphy	Varved records	Tephrochronology	Age modelling	INTIMATE protocols	Climate Models
1995		Limited to 10,100 cal BP (Becker and Kromer, 1986)	Several GISP2 and GRIP age models (Grootes et al., 1993)		Icelandic ash found in Greenland ice (Grönvold et al., 1995)	Bayesian methods introduced for <sup>14</sup> C calibration (Bronk Ramsey, 1995)		
1996				Cariaco Basin varved record for last cold stage developed (Hughen et al., 1996)		Wiggle matching to the dendro-calibration curve introduced (Björck et al., 1996)		
1997					Microtephra (later <i>cryptotephra</i> ) found in Lateglacial sediments (Lowe and Turney, 1997)			
1998	IntCal98 Marine98 (Stuiver et al., 1998)	Extended to 10,340 cal BP (Friedrich et al., 1999)		Dated Cariaco Basin record tied to dendro <sup>14</sup> C record (Stuiver et al., 1998)		Age of the Younger Dryas – Holocene boundary determined by wiggle matching (Gulliksen et al., 1998)	INTIMATE Event stratigraphy introduced (Björck et al., 1998)	Comparison of simulated and proxy-based Younger Dryas temperatures in Europe (Renssen and Isarin, 1997)
1999			Adoption of the GRIPss08c timescale (Walker et al., 1999)	Calendar year chronology from Meerfelder Maar (Brauer et al., 1999)				
2001				Holzmaar and Meerfelder varves compared (Brauer et al., 2001)	Expansion of cryptotephra research proposed (Turney et al., 2004)		Event stratigraphy based on ss08c timescale (Lowe et al., 2001)	
2003		Extended to 12,410 cal BP (Friedrich et al., 2004)			Monticchio tephra archive developed for last 100 ka (Wulf et al., 2004)			
2004	IntCal04 Marine04 (Reimer et al., 2004)				Cryptotephra 'footprints'	Bayesian-based analysis of	(Crypto-) tephrochronology	

	al., 2004)				extended over Europe (Turney et al., 2004)	European lateglacial sequences (Blockley et al., 2004)	introduced in INTIMATE event stratigraphy (Turney et al., 2004)	
2005			GICC05 timescale developed to 14.8 ka b2k and adopted (Rasmussen et al., 2006)		Volcanic ash layers in NGRIP lateglacial (Mortensen et al., 2005)			
2006			GICC05 extended to 42 ka b2k (Andersen et al., 2006; Svensson et al., 2006)					
2007								Last Glacial Maximum simulation intercompared with proxy based reconstructions (Roche et al., 2007a)
2008		Extended to 12594 cal BP (Schaub et al., 2008)	GICC05 extended to 60 ka b2k (Svensson et al., 2008) and applied to GRIP and GISP2 to 32 ka b2k (Rasmussen et al., 2008)			Bespoke models for age-depth modelling developed (Bronk Ramsey, 2008)	Event stratigraphy based on GICC05 and extended to 30 ka (Lowe et al., 2008)	
2009	IntCal09 Marine09 (Reimer et al., 2009)							
2010			The layer-counted GICC05 extended by ice flow modelling results to form the GICC05modelext time scale (Wolff et al., 2010)		Linking of NGRIP to North Atlantic marine sequences using tephra isochrones (Davies et al., 2010)			Intercomparison of different Last Glacial Maximum simulations
2011					Robust linking of NW Europe and Mediterranean cryptotephra archives (Lane et al., 2011)			First transient deglacial simulations produced (Roche et al., 2011)

2012		Extended to early Bølling, but with gap (Kaiser et al., 2012)	GICC05 applied to GRIP to 48 ka b2k (Blockley et al., 2012)	Continuous varve record obtained from Lake Suigetsu (Nakagawa et al., 2012)	Monticchio tephra archive extended to 133 ka (Wulf et al., 2012)		Event stratigraphy extended to 48 ka (Blockley et al., 2012)	First intercomparison of three transient deglaciation simulations
2013	IntCal13 Marine13 (Reimer et al., 2013)			Suigetsu record included in IntCal13; Norwegian and German varves synchronised (Lane et al., 2013)				First evaluation of a transient deglacial simulation with fully coupled water isotopes (Caley et al., 2014)
2014			GICC05mod elect applied to entire uncompromised length of GRIP and GISP2 (Seierstad et al., in this issue)		North Atlantic tephrostratigraphic framework extended to 130 ka (Davies et al., in this issue)	INTIMATE database with time-scale transform function developed (Bronk Ramsey et al., in this issue)	Event stratigraphy extended throughout the Glacial (Rasmussen et al., in this issue)	First direct ice-core to model evaluation for last glacial cycle with water isotopes (Roche et al., in this issue)

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