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The importance of independent chronology in integrating records of past climate change for the 60–8 ka INTIMATE time interval

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ABSTRACT

This paper provides a brief overview of the most common dating techniques applied in palaeoclimate and palaeoenvironmental studies including four radiometric and isotopic dating methods (radiocarbon, ^{230}Th disequilibrium, luminescence, cosmogenic nuclides) and two incremental methods based on layer counting (ice layer, varves). For each method, concise background information about the fundamental principles and methodological approaches is provided. We concentrate on the time interval of focus for the INTIMATE (Integrating Ice core, MArine and TErrestrial records) community (60–8 ka). This dating guide addresses palaeoclimatologists who aim at interpretation of their often regional and local proxy time series in a wider spatial context and, therefore, have to rely on correlation with proxy records obtained from different archives from various regions. For this reason, we especially emphasise scientific approaches for harmonising chronologies for sophisticated and robust proxy data integration. In this respect, up-to-date age modelling techniques are presented as well as tools for linking records by age equivalence including tephrochronology, cosmogenic ^{10}Be and palaeomagnetic variations. Finally, to avoid inadequate documentation of chronologies and assure reliable correlation of proxy time series, this paper provides recommendations for minimum standards of uncertainty and age datum reporting.

1. Introduction

It is commonly accepted that the wealth of information about climate change and environmental responses recorded in various sedimentary deposits can only be adequately utilised when it is placed into a robust chronological framework. In recent decades the demands for precise and accurate chronologies has rapidly increased since it has been realised that climate changed not only on time scales of tens or hundreds of thousands of years, but that climate changes even occurred over less than a human lifetime. Therefore, in modern Quaternary science, information on the timing of past changes is needed, i.e. how much time passed during a shift from one climatic state to another or between different climatic shifts. This will further allow investigation of various mechanisms of climate change in relation to the time scales on which they occur.

Another emerging challenge for palaeoclimate research, and in particular for the INTIMATE community, is tracing potential leads and lags in regional climate response to global change and their possible driving mechanisms. Since such regional disparities in climate change are likely to be in the range of sub- to multi-decadal rather than millennial time scales, an extremely precise correlation of different records from different regions is essential for detection of such leads and lags. However, currently records are often still synchronised through wiggle-matching of proxy data based on the assumption that climatic changes always occur contemporaneously,

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although it has been demonstrated that climate change may be spatially and temporally time-transgressive (Lane et al., 2013). Moreover, climate records derived from different proxies are often wiggle-matched neglecting different temporal responses by those proxies (e.g. pollen in terrestrial records and stable isotopes in Greenland ice cores) with some proxies responding to climate shifts more rapidly than others do. In practice, the concept of assuming general synchronicity of climate change and proxy response to climate changes prevents the tracing of potential leads and lags in regional climate and proxy response times. However, independent integration of palaeoclimate records from different regions is not a trivial task and requires major efforts in both reducing uncertainties in individual chronologies, and in developing robust synchronisation tools. In future, this will attract even more attention with increasing attempts to integrate climate archives over larger regions such as those shown in this issue for the Alps (Heiri et al., in this issue), Western Europe (Moreno et al., in this issue) and Eastern Europe (Feurdean et al., in this issue).

The great diversity of sediment archives and related dating techniques, partly based on fundamentally different concepts (e.g. isotopic/radiometric *versus* layer counting), as well as the rapid technical progress, makes it increasingly difficult for non-specialists to keep track of the various dating approaches and their inherent uncertainties when using them for correlation purposes. This paper aims to provide a brief guide to the most commonly used dating methods for palaeoclimate records within the INTIMATE time frame of 60–8 ka, outlining the fundamental methodological principles, the inherent sources of uncertainty, and discussing the reporting of ages. This guide is intended to provide basic information and references relevant for applying chronologies but does not replace comprehensive reviews for individual dating methods (e.g. Walker, 2005).

Moreover, this paper provides an inventory of age reporting protocols applied by the different contributing dating communities with a particular focus on the reference year, or datum, used. Since this is a controversial issue and recommendations of defining a common datum for all dating methods (cf. Wolff, 2007) have not yet been commonly accepted, an overview on how each dating community deals with this problem is provided below.

2. Overview of dating methods

As mentioned above, we will not present a comprehensive list of all available dating methods, but focus on the most common geological dating methods applied for the INTIMATE time frame of 60–8 ka, which include traditional methods such as radiocarbon dating and layer counting (varves and ice), but also recently emerging and rapidly evolving methods such as luminescence and exposure age dating. The latter play an important role in complementing classical INTIMATE palaeoclimate archives like marine and lake sediments or ice cores with geomorphic features like, for example, moraines and dunes or sand sheets. We divide this paper into isotopic or radiometric dating on discrete samples, followed by incremental dating based on continuous layer counting and the latest age modelling approaches.

2.1. Radiocarbon based chronologies

Radiocarbon (^{14}C) dating, a method that was established by Willard Libby and co-workers (Libby et al., 1949; Arnold and Libby, 1951), has been applied to dating natural archives for more than six decades. It has been employed in climate research from the early days of the method (Olsson, 2009 and references therein). Chronologies of marine and terrestrial records of past climate were first established using counting of beta particles, i.e. the product of the decay of ^{14}C atoms. With the development of accelerator mass spectrometry (AMS) in the 1970s sample size requirements were reduced dramatically allowing for higher resolution studies, which led to an expansion of the field (see summary by Povinec et al., 2009). The first attempts to reconstruct the chronology of the deglaciation (Lateglacial) in the North Atlantic region relied heavily on ^{14}C dating. Prior to the INTIMATE programme, the IGCP-253 North Atlantic Region program utilised ^{14}C dating to correlate the timing of climatic changes that took place during the Lateglacial in the North Atlantic region (Lowe et al., 1994). Twenty years later, various improvements in the radiocarbon method have been realised. Among these is a reduction of sample size from 1 mg of carbon to only tens of micrograms of carbon (Ruff et al., 2010), improved precision of AMS analyses (Synal et al., 2007; Synal and Wacker, 2010), extension of the calibration curve (Reimer et al., 2013) and development of calibration software (Aitchison et al., 1989; Bronk Ramsey, 1995; Buck et al., 1999; Blaauw et al., 2003).

The great value of ^{14}C dating is that the method can be applied to any carbon bearing material – meaning that the samples of direct interest may be analysed. Commonly dated substances include: cellulose-containing materials (wood, seeds, plant remains); charcoal and charred material; carbonates (including speleothems, foraminifera, shells); collagen-containing materials (bone, tooth, antler, and ivory); hair; and, bulk sediment. Given its broad applicability and the extensive development of the technique over the last six decades, ^{14}C remains the most commonly applied scientific dating method available for sample materials up to 50 thousand years old.

2.1.1. ^{14}C dating method

Of the three naturally occurring carbon isotopes, ^{14}C is the only one to be radioactive and has a half-life ($t_{1/2}$) of 5730 ± 40 yrs (Godwin, 1962). Concentration of this cosmogenic isotope (produced in the atmosphere by cosmic rays) is very low (i.e., $^{14}C/^{12}C \sim 10^{-12}$). Oxidised to CO_2, atoms of ^{14}C enter the global carbon cycle and become incorporated into carbon-bearing material that can later be used for dating (Libby et al., 1949). An accurate ^{14}C age requires that the carbon isolated from the sample is representative of the material at the time of deposition. Various methods of sample preparation and measurement have been developed over the years allowing for more accurate and precise chronologies of natural archives (for overview see Hajdas, 2008 and references therein).

2.1.2. ^{14}C age calculation, corrections, and reporting of results

Measured radiocarbon concentrations, determined either by counting methods (decay) or by AMS (counting ^{14}C atoms), result in conventional radiocarbon ages that have been calculated using the original Libby half-life (5568 years) (Table 1) (Stuiver and Polach, 1977; Mook and van der Plicht, 1999; Reimer et al., 2004). It is important to note that all conventional ^{14}C ages include a fractionation correction (i.e., a $\delta^{13}C$ based correction for mass fractionation of ^{14}C atoms that occurs through natural bio-geochemical processes as well as during sample preparation and measurement). By convention, all data are corrected to −25‰, a representative $\delta^{13}C$ value for wood (Stuiver and Polach, 1977).

Radiocarbon ages are reported with $\pm 1\sigma$ uncertainty (reflecting counting statistics, correction for blanks and standards) in ^{14}C yrs BP (Before Present = A.D. 1950). Laboratory sample IDs, which are given to the samples by the radiocarbon dating laboratory, enable the laboratory to be identified and should always be published alongside the ^{14}C measurements.

2.1.3. Calibration of radiocarbon ages

Natural variability in the concentration of atmospheric ^{14}C caused by changes in production rate and exchange between reservoirs of carbon (atmosphere-ocean), and an underestimated

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