

## SELECTION AND TREATMENT OF DATA FOR RADIOCARBON CALIBRATION: AN UPDATE TO THE INTERNATIONAL CALIBRATION (INTCAL) CRITERIA

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**ABSTRACT.** High-quality data from appropriate archives are needed for the continuing improvement of radiocarbon calibration curves. We discuss here the basic assumptions behind <sup>14</sup>C dating that necessitate calibration and the relative strengths and weaknesses of archives from which calibration data are obtained. We also highlight the procedures, problems, and uncertainties involved in determining atmospheric and surface ocean <sup>14</sup>C/<sup>12</sup>C in these archives, including a discussion of the various methods used to derive an independent absolute timescale and uncertainty. The types of data required for the current IntCal database and calibration curve model are tabulated with examples.

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## INTRODUCTION

Radiocarbon dating provides the chronological basis for much archaeological and geoscientific research in the late Quaternary period. A  $^{14}\text{C}$  age, however, does not provide a calendrical age directly but must be corrected for variations in the  $^{14}\text{C}/^{12}\text{C}$  ratio of the atmosphere, ocean, or other reservoir where the sample grew or was formed. This is done by comparison (i.e. calibration), with curves derived from  $^{14}\text{C}$  ages of samples that have been calendrically dated by alternative and independent means. In the best-case scenario, the calendar age of the independently dated samples should be known precisely and absolutely. Numerous such calibration curves have been constructed over the years (see reviews in Klein et al. 1982; Becker 1992; Reimer and Reimer 2007). These have evolved through time as new calibration data sets have become available and improved data analysis techniques have been implemented. The importance of a standardized calibration curve for specific reservoirs, which, amongst other advantages, makes direct comparison between studies feasible, has been acknowledged by the international  $^{14}\text{C}$  community (Klein et al. 1982; Turney et al. 2006).

The IntCal Working Group (IWG) grew out of earlier collaborations between researchers who provided the data used to construct the 1993 and 1998 calibration curves (Stuiver and Reimer 1993; Stuiver et al. 1998a,b). The IWG has provided 2 major updates and extensions to the terrestrial and marine calibration curves, which have been ratified at International Radiocarbon conferences (Hughen et al. 2004; Reimer et al. 2004, 2009). The calibration curves presented in this issue were ratified in 2012 at the 21st International Radiocarbon Conference in Paris. The IWG comprises researchers actively interested in a wide variety of facets associated with  $^{14}\text{C}$  calibration, including the production of calibration data sets, assessment of the variability in  $^{14}\text{C}/^{12}\text{C}$  ratios in specific reservoirs or at specific localities over time, statistical interpretation of information from a varied ensemble of large data sets, or application of calibration in archaeological and environmental studies. The IWG does not have a fixed composition and consists of individuals who are working actively to refine  $^{14}\text{C}$  calibration including major data providers, modelers, and those who have been involved in previous IntCal exercises. The IntCal Oversight Committee was nominated and elected by the user community in 2008 and contributes to the decision-making processes of the IWG.

The IWG published criteria for the inclusion of data into the international  $^{14}\text{C}$  calibration curves in Reimer et al. (2002) to promote discussion and involvement from the wider community in the process of producing consensus calibration curves. Over the course of the past decade, advances in statistical methods used to construct the calibration curve (Blackwell and Buck 2008; Heaton et al. 2009; Niu et al. 2013, this issue), and careful refinement of the scientific methods used to produce calibration data, mean that it is now possible to quantify and formally allow for a much wider range of sources of uncertainty and offset from a diverse range of archives. We are acutely aware that there will be further advances in this field, with inevitable adjustment of curves as more calibration-quality data emerge and alternative compilation methods are promoted. Critical to such efforts will be the adoption of a consistent and thorough approach to documentation of all sources of uncertainty and methodological procedures and a range of metadata to enhance the long-term value of individual data sets. Given the recent rapid increase in the number of calibration data sets and the inevitable changes, the IWG feels this is an appropriate time to provide updated criteria for calibration-quality data, and the types of metadata desirable for data sets contributing to future calibration curves.

We will discuss the following in this article:

1. Basic assumptions behind  $^{14}\text{C}$  dating that necessitate calibration;
2. Archives from which calibration data are obtained;

3. Procedures used to determine the sought-after  $^{14}\text{C}/^{12}\text{C}$  (of atmosphere or mixed surface ocean);
4. Methods to derive an independent absolute timescale for the  $^{14}\text{C}$  calibration data obtained from the respective archives and the associated uncertainties.

### RADIOCARBON DATING AND CALIBRATION

An uncalibrated  $^{14}\text{C}$  age calculation includes several assumptions: 1) Atmospheric  $^{14}\text{C}/^{12}\text{C}$  has been constant through time; 2) The carbon reservoir in which the sample grew or was formed had the  $^{14}\text{C}/^{12}\text{C}$  composition of the atmosphere or had a known offset with respect to it; and 3) The sample came from a closed system that has not exchanged carbon with its surroundings since formation.  $^{14}\text{C}$  calibration is intended to correct for any violation of the first 2 assumptions through the use of curves constructed from measurements on appropriate archives, which also must satisfy the last assumption.

The Northern Hemisphere atmospheric reservoir is the best understood, with pre-industrial  $^{14}\text{CO}_2$  relatively well mixed, in theory, and derived  $^{14}\text{C}$  ages expected to deviate significantly at only high altitude or latitude (Braziunas et al. 1995). Regional differences on the order of 10–20  $^{14}\text{C}$  yr have been observed due to coastal upwelling of older,  $^{14}\text{C}$ -depleted ocean carbon, or due to growing-season differences (Stuiver and Braziunas 1998; Kromer et al. 2001; Dee et al. 2010). The Southern Hemisphere atmosphere has a stronger latitude dependency due to the larger ocean to land surface area ratio combined with the upwelling of older water around Antarctica and the strong circumpolar winds (Braziunas et al. 1995). At mid-latitudes, the Southern Hemisphere  $^{14}\text{C}$  has differed from the Northern Hemisphere, on average, by approximately 45  $^{14}\text{C}$  yr for the last 2 millennia, but varies between –12 and +83  $^{14}\text{C}$  yr (Hogg et al. 2009, 2011). The atmospheric record in low latitudes in both the Northern and Southern hemispheres is also complicated by the Intertropical Convergence Zone (ITCZ), where the winds from the 2 hemispheres come together, making atmospheric mixing across this zone irregular. The position of the ITCZ varies with the changing seasons and over longer time periods, so some low-latitude locations may sporadically reflect either Northern or Southern atmospheric  $^{14}\text{C}$  (e.g. Hua et al. 2004; Wang et al. 2004).

The carbon in the surface ocean (marine mixed layer) is a mixture of  $\text{CO}_2$  recently exchanged with the atmosphere and older  $\text{CO}_2$  diffused upwards from the thermocline and the deep ocean. In the current ocean circulation regime, this produces an average  $^{14}\text{C}$  offset from the atmosphere of approximately 400 yr (called the global ocean reservoir offset), but the actual offset varies with location, especially in regions of upwelling of older ocean water such as Antarctica, the west coasts of continents, or in regions where large baroclinic eddies may be generated (Bard 1988; Stuiver and Braziunas 1993; Levin and Heshaimer 2000). In general, the range of decadal-scale  $^{14}\text{C}/^{12}\text{C}$  variations in the marine mixed layer is attenuated relative to that observed in the atmosphere, although some corals have been shown to track the atmosphere closely (Druffel et al. 2008). The reservoir offset is also variable over time, particularly during periods when ocean circulation was different from present, such as during the last glaciation and in the North Atlantic during the Younger Dryas and Heinrich cold events (Bard et al. 1994; Austin et al. 1995, 2011; Hafliadason et al. 2000; Voelker et al. 2000; Bondevik et al. 2006). These reservoir offsets have been simulated in modeling exercises (e.g. Butzin et al. 2005; Franke et al. 2008; Singarayer et al. 2008; Matsumoto and Yokoyama 2013).

### ARCHIVE SELECTION

Several factors challenge the exercise of deriving a robust calibration curve from a suite of calibration data sets. Key amongst these factors are the integrity of the samples used in the  $^{14}\text{C}/^{12}\text{C}$  data set (e.g. closed systems, stratigraphically consistent) and secondly, the quality of the independent time-

scale. Much work has been expended in the past to generate high-quality  $^{14}\text{C}$  measurements on records that were later shown to deviate from other calibration records well beyond statistical uncertainties. The Swedish varved clays (Wohlfarth and Possnert 2000) and the initial single Lake Suigetsu core (Kitagawa and van der Plicht 1998; Staff et al. 2010) are 2 examples where hiatuses in sediments caused deviations in the timescales. Therefore, care must be taken in selecting an archive and establishing a reliable timescale, although problems may not be recognized until comparisons to other records are made.

When selecting an archive as a representative recorder of  $^{14}\text{C}$  variation for calibration of one of the carbon reservoirs (i.e. atmosphere or ocean), the relationship between what is measured and how an atmospheric or ocean mixed layer signal was incorporated into this sample must be considered (e.g. ocean reservoir age, dead carbon fraction, seasonality, bioturbation). For any marine archive, the regional reservoir offset and its variability over time must be evaluated, regardless of whether the data are used to construct an “atmospheric equivalent” or a normalized “global” marine calibration curve. Records should originate from hydrodynamically simpler regions (e.g. away from coastal and open ocean upwelling zones or where the currents are complex and climatically sensitive).

In general, high-resolution data (e.g. samples formed in 10 yr or less in the Holocene and deglaciation and 50 yr or less in the glacial period) are preferred to low-resolution data (>50 yr resolution), because of the extra information that they carry, particularly regarding any inversions or rapid inflections in the curve. In addition, clear evidence of reproducibility needs to be supplied and, in particular, within the uncertainties given (an overlap with existing calibration data is useful in confirming this). There must also be quality control on the associated calendar age estimates, with sufficient information provided on how errors were constructed, to offer confidence that efforts were made to identify and, where practical, quantify all sources of uncertainty on the observations jointly as well as individually.

### **Tree Rings**

Tree rings are ideal recorders of atmospheric  $^{14}\text{C}$  and are most useful in estimating the calibration curves if the ring widths series of the relevant trees can be compiled up to the present as an independent absolute chronology, or be robustly correlated to an independently established tree-ring chronology of matchable species and climatically similar region (Becker 1992). In such cases, tree rings provide a reliable absolute annually resolved chronology as opposed to a floating one. Trees from the mid- and high latitudes—where sites of the long chronologies are located—reliably form exactly 1 ring per year (e.g. St. George et al. 2013). Sporadic missing or double rings can occur in some species relevant to long dendrochronologies but can be detected through use of multiple replications of the tree-ring series (Spurk et al. 1998; Palmer et al. 2006). Therefore, multiply-replicated tree-ring chronologies are generally thought to be one of the most reliable and accurate timescales (Becker 1992).

The cellulose in tree rings is formed primarily from photosynthesis in a single growing season with a component coming from carbon stored from previous years (Grootes et al. 1989). Alpha- or holo-cellulose extraction has been used for many years but not for all tree-ring calibration samples. Measurements on material extracted from tree rings of Douglas fir growing through the peak of atmospheric nuclear weapons testing in the early 1960s indicated deposition of material with high  $^{14}\text{C}$  activity into wood formed up to 40 yr earlier (Stuiver and Quay 1981). The de Vries method of sample pretreatment (heating in NaOH and HCl solutions; de Vries and Barendsen 1952) is often used for tree-ring  $^{14}\text{C}$  measurements but does not remove all of the compounds such as lignin that may be incorporated into the tree-ring wood after cell formation (Cain and Suess 1976). However, the  $^{14}\text{C}$  activity of de Vries-treated Douglas fir wood did not differ statistically from those treated to alpha-

cellulose, except for rings formed within 20 yr of the nuclear weapons testing peak (Stuiver and Quay 1981). Therefore, except for unusual periods of extreme, rapid change in atmospheric  $^{14}\text{C}$  content (like the bomb pulse) or at the older end of the  $^{14}\text{C}$  timescale (Hogg et al. 2006; Turney et al. 2010), the de Vries and alpha-cellulose pretreatment methods produce only small differences in  $^{14}\text{C}$  abundance generally within measurement uncertainty.

### Terrestrial Macrofossils

Terrestrial macrofossils can also be suitable for direct recording of atmospheric  $^{14}\text{C}$  if an independent timescale can be established (e.g. Bronk Ramsey et al. 2012), although it is also recognized that organic material can sometimes remain in the landscape for a considerable length of time before being deposited, particularly in high-latitude environments, or be reworked from earlier deposits (Abbott and Stafford 1996; Oswald et al. 2005). For this reason, fragile leaves and plant fragments without evidence of reworking are the preferred material (Barnekow et al. 1998; Turney et al. 2000). In lake sediments, preference should be for intact fragile terrestrial macrofossils. Some emergent aquatic plants take up some  $\text{CO}_2$  from the sediments and shorter riparian plants can utilize  $\text{CO}_2$  evading from the surface water, either of which could result in older apparent  $^{14}\text{C}$  ages due to incorporation of geological or remineralized organic carbon (Maberly and Spence 1983; Boston 1986; Hatté and Jull 2007). In tectonically active regions, lakes may also be affected by magmatic  $\text{CO}_2$  devoid of  $^{14}\text{C}$ . In such lakes, wind-blown terrestrial macrofossils are typically free of old C (e.g. Lago di Monticcio, Hajdas et al. 1998). While terrestrial pollen may also be extracted from sediments for  $^{14}\text{C}$  analysis, aquatic pollen spores and non-pollen palynomorphs, which may be subject to a lake reservoir effect, and reworked pollen are difficult to avoid, though new methods offer considerable promise (Tennant et al. 2013).

For terrestrial macrofossils, an independent, precise, and accurate timescale for sediments can be difficult to establish, and usually requires annually laminated (varved) sediments (see section “Varve Counting”) in combination with tephrochronology and/or correlation of preserved and assumed regionally synchronous climate signals. A combination of high-resolution micro-XRF (Marshall et al. 2012) with microscopic sedimentary analysis and an algorithm to interpolate indistinguishable varves (Schlölaut et al. 2012), such as those used for the Suigetsu core SG06 (Bronk Ramsey et al. 2012), may provide floating chronologies of sufficient quality that they can be made absolute by anchoring them to the secure part of the atmospheric tree-ring calibration curve.

### Corals

Aragonitic coral species that grow near the surface of the ocean have provided  $^{14}\text{C}$  records of the marine mixed layer in specific regions (e.g. Bard et al. 1990a for the Atlantic; Edwards et al. 1993 for the Pacific). Many  $^{14}\text{C}$  measurements on U-Th dated corals have been included in the international  $^{14}\text{C}$  calibration curves since 1993. Criteria for screening for corals that meet the closed system requirement have been discussed in detail previously (Reimer et al. 2002, 2004, 2006; Chiu et al. 2005) and relate to the preservation of the primary mineralogy and negligible gain or loss of U, Th, or C isotopes by any means other than radioactive decay since the time of formation. The IntCal coral criteria are summarized below.

Any calcite present in the aragonitic corals is presumed to be secondary in nature (Chappell et al. 1974). Depending on the environment, surface contamination from calcite can be older, younger, or contemporaneous to the coral, as in the case of overgrowths by coralline algae and/or by microbials (e.g. Seard et al. 2010). As such, quantitative X-ray diffraction measurements should show <1% calcite. This implies an even lower detection limit, typically around 0.2% (e.g. Chiu et al.

2005; Sepulcre et al. 2009). Alternatively, independent evidence of the reliability of the sample material should be produced.

The geochemistry of calcite overgrowths influences whether it is more soluble (high Mg) or less soluble (low Mg) than aragonite (Morse and Mackenzie 1990; Railsback 2006; Andersson et al. 2008; Andersson and Mackenzie 2011), but in most cases leaching removes surface contamination (Bard et al. 1990b; Burr et al. 1992; Yokoyama et al. 2000; Durand et al. 2013, this issue). We therefore recommend that each coral sample be acid-leached prior to  $^{14}\text{C}$  dating to remove surface contamination, that the residual calcite content after leaching be below 1%, and that measured values are provided with the  $^{14}\text{C}$  age. We advise that specific tests are performed to quantify the influence of residual contaminations at a particular sampling site of corals, notably the age of secondary carbonates (calcite or aragonite) and their efficient removal by leaching or other techniques. Future research may lead to the adoption of new stringent criteria (general or site-specific).

The U concentration of fossil corals should be similar to modern specimens taking into account the variability observed today (interspecific differences and dependency to environmental parameters such as growth temperature). Initial  $^{234}\text{U}/^{238}\text{U}$  values of Holocene and deglacial fossil corals should lie within the modern and recent corals range corresponding to  $\delta^{234}\text{U} = 147 \pm 7 \text{‰}$  (3 s.d.). Last glacial period corals tend to record  $\delta^{234}\text{U}_{\text{initial}}$  values 7–10‰ lower than modern (Cutler et al. 2004; Esat and Yokoyama 2006; Durand et al. 2013, this issue). Whether this difference results from diagenesis or a shift in the marine value is not absolutely clear (Cutler et al. 2004; Robinson et al. 2004; Esat and Yokoyama 2006). However, to allow for the latter possibility, corals >17 kyr BP should be within the range of  $142 \pm 8 \text{‰}$  (3 s.d.). Note that the higher end of this range encompasses the modern value.

### **Forams**

The carbonate shells of planktonic foraminifera can provide a  $^{14}\text{C}$  record of the marine mixed layer in specific regions, depending on the preferred depth habitat and seasonal life cycle. With forams from non-varved sediments, the issue of bioturbation must be considered also (Bard et al. 1987; Thomson et al. 1995; Löwemark and Grootes 2004); hence, high sedimentation records (e.g. over 20 cm/1000 yr) are preferred for inclusion in consensus calibration curves. It is also recognized that the deposition of older reworked shells can be problematic (Heier-Nielsen et al. 1995), although abundance and the degree of preservation of the chosen species can be used as important indicators of reworking (Barker et al. 2007). With the exception of varved sediments, high-resolution chronologies for foram-based records must be derived from established atmospheric teleconnections with minimal lag to independent and accurately dated archives such as ice cores with annual layer counting or speleothems dated by U-Th (Voelker et al. 2000; Bard et al. 2004; Hughen et al. 2006). Uncertainties of the derived absolute timescale should be estimated from propagation of the uncertainties of both the original absolute chronology (see section “Uranium-Thorium Dating”) and of the correlation process between both climatic signals (see section “Tie-Pointed Timescales”) (Hughen et al. 2006; Bard et al. 2013, this issue; Heaton et al. 2013, this issue). As for corals, the use of a mixed-layer record as an atmospheric equivalent requires quantification of the local surface  $^{14}\text{C}$  reservoir age and its possible variations over time (Bard 1988; Stuiver and Braziunas 1993; Sarnthein et al. 2007, 2013).

### **Speleothems**

Speleothems are secondary mineral deposits that precipitate from drip water in caves. Calcite and aragonite, polymorphs of calcium carbonate, dominate the various mineral formations (e.g. stalag-

mites, stalactites, and flowstones), with coarsely crystalline examples of calcite the most likely to be closed systems and thus suitable for  $^{14}\text{C}$  calibration. At the time of formation, U from the ground water is coprecipitated in calcite and aragonite, with negligible Th. The ingrowth of the radiogenic daughters  $^{230}\text{Th}$  and  $^{231}\text{Pa}$  can be used to provide an independent timescale using U-Th-Pa methods. Dissolved inorganic carbon in cave drip water is sourced from a combination of root respiration, soil organic matter decomposition, the cave air, and dissolution of bedrock (Genty et al. 2001; Baldini 2010). Decomposition of soil organic matter may have a time lag between growth of the plants and its remineralization and incorporation in groundwater, affecting  $^{14}\text{C}$  levels in the speleothem, particularly during periods when climate and vegetation changed (Genty et al. 2001). This effect is likely to contribute offsets of years to perhaps decades, but is minor compared with the expected contribution of  $^{14}\text{C}$ -free carbonate from the bedrock—the dead carbon fraction (DCF) or dead carbon proportion (dep), which can vary dramatically between different locations in the cave, and sometimes during the period of growth (Genty et al. 2001). For speleothems, a correction for DCF and its variability through time has to be made to estimate “atmospheric equivalent”  $^{14}\text{C}$  concentration for calibration purposes. DCF is usually estimated by analyzing a section of the speleothem that overlaps with the tree-ring portion of the calibration curve. The mean  $^{14}\text{C}$  offset from the established calibration curve is then used as the DCF. An uncertainty term associated with the variance between the speleothem and established calibration curve, which is usually as large as or larger than the analytical uncertainty terms, must also be added quadratically to the other analytical uncertainties. Considering the potential effect of the interplay between vegetation and climate (temperature, precipitation) on soil carbon and drip rates, an assumed constant  $^{14}\text{C}$  offset is probably a simplification of the actual situation. Establishing the reliability of the absolute timescale obtained by U-Th dating requires a careful evaluation similar to that described above for corals, based on stratigraphic consistency and replicate analysis (see later section for further details on uncertainties associated with U-Th-derived timescales). Age-depth models have been utilized because the speleothem growth rate is non-uniform and subsamples for  $^{14}\text{C}$  dating may be obtained at different intervals to those used for U-Th dating. In so doing, then, calendar ages are based on interpolation at depths sampled for  $^{14}\text{C}$  determination. Uncertainty of the calendar age for a corresponding  $^{14}\text{C}$  age will be influenced by U-Th age errors, density of U-Th determinations along the growth axis, and expected growth rate variation (see also section “Age-Depth Models”).

### Other Potential Archives

It is expected that a wider range of data sets will be considered for inclusion in the IntCal database. One possibility is plant material (e.g. trees), charred in volcanic eruptions for which tephra have been dated using  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  methods. In such circumstances, the outer tree rings or short-lived organic material are assumed to be contemporaneous with the eruption. This is only feasible in volcanic eruptions with potassium-rich tephra. Care would need to be taken that the plant material was not living close to the active volcano since  $^{14}\text{C}$ -depleted  $\text{CO}_2$  can be emitted from volcanic activity (Sulerzhitzky 1971; Rubin et al. 1987; Pasquier-Cardin et al. 1999). Correlation with well-dated (e.g. macrofossils) distal deposits may be the best approach to overcome this problem.

Specific compounds can also be extracted from marine and terrestrial sediments and analyzed, providing an alternative source for marine or atmospheric  $^{14}\text{C}$  content. Preference should be given for a compound specific to a single species rather than poorly differentiated compound series (e.g. alkanes) that are a mixture of compounds from different origins (and thus, potentially, different  $^{14}\text{C}$  activities). Care should also be taken to ensure an adequate sample size to avoid reduced precision during measurement. As with non-varved terrestrial macrofossil and foraminifera records, the timescale for non-varved sediments must be derived from correlations of climate proxies with inde-

pendently dated climate series (such as  $\delta^{18}\text{O}$  in ice cores or speleothems). The resulting timescale should be tested with event markers, such as tephra horizons, where possible, or checked for plausible sedimentation rates.

## PROCEDURES

### $^{14}\text{C}$ Sample Pretreatments, Blanks, and Interlaboratory Comparisons

Sample pretreatments should also account for the chemical and physical structure of the target carbon to ensure that the pretreatment removed any natural contamination and did not add significant levels in the laboratory. This can be a problem especially during alkali treatment for macrofossils (Hatté et al. 2001) or charred organic material (Ascough et al. 2009; Higham et al. 2009; Douka et al. 2010). Pretreatments should follow well-established techniques or demonstrate that the technique used is suitable. The pretreatment should be specified in the metadata (Table 1).

Background or blank determination is necessary to account for any sample processing contamination or machine noise in  $^{14}\text{C}$  measurements. Anthracite was commonly measured for the background for organic samples in the past, whereas material closer in morphology and depositional environment to the samples is preferred where possible (e.g. wood or charcoal). Geological calcite may be used when measuring carbonate samples, although here too blank material similar to the sample material is to be preferred. The selection of the background material becomes even more important when measurements are made close to the limit of the  $^{14}\text{C}$  method. *In situ* contamination may be more difficult to remove in some materials, so the use of background samples of similar material may give a more representative blank value. For carbonates such as foraminifera or marine shells, the background may be species-dependent, so it is advisable to process at least some background samples (>80 ka) of the same species and provenance when measuring older samples (>30 ka) (Nadeau et al. 2001). Where speleothem material >>50 ka is available from the same sample or cave setting, one can use this to reproduce typical analytical blanks, but we recognize that some material may be susceptible to postdepositional alteration because of higher porosity. In addition, sample preparation needs to be considered carefully for all material to reduce analytical blanks. For example, Beck et al. (2001) observed that powdered calcite samples drilled from some stalagmites had consistently higher  $^{14}\text{C}$  concentrations than wafers of the same age material, and this could only be explained by difference in surface area and resultant adsorption of modern  $^{14}\text{C}$  prior to analysis.

The  $^{14}\text{C}$  community has devoted considerable care and effort to establishing and maintaining primary standards and reference materials and in the routine organization of laboratory inter-comparisons or proficiency trials to verify comparability of measurements. From such a series of collaborative trials, secondary standards or reference materials have been developed, including internationally recognized materials such as ANU sucrose (also known as IAEA-C6), Chinese sucrose, and the IAEA C1–C6 series (Rozanski et al. 1992), augmented by additional oxalic acid samples (now IAEA C7 and C8) (Le Clercq et al. 1998). The activity of these materials has been estimated from large numbers of measurements made by many laboratories. Further natural materials from the Third and Fourth International Radiocarbon intercomparisons TIRI (Gulliksen and Scott 1995) and FIRI (Bryant et al. 2001; Scott 2003), and now VIRI (Scott et al. 2010a) have been added to this list. These standards and reference materials span both the applied  $^{14}\text{C}$  age range and the chemical and biological composition range of typical samples. A summary of the intercomparisons organized within the  $^{14}\text{C}$  dating community can be found in Scott (2003) and Scott et al. (2010a). The results from the most recent intercomparisons have indicated that laboratories are in general providing accurate results, but have pointed to variation in the results beyond that



described by the quoted errors. This provides some evidence that the quoted errors are, on occasion, overestimates of the precision for some laboratories.

Recently, the <sup>14</sup>C community completed the Fifth International Intercomparison (VIRI), continuing the tradition of the TIRI (third) and FIRI (fourth) intercomparisons as a <sup>14</sup>C community project, with samples provided by participants and a substantial participation rate. VIRI was designed to have 3 stages, spread over several years, involving 2 sets of specific sample types (grain and bone) and then a final stage involving a wide variety of common sample materials. Reports on each stage have been published (Scott et al. 2010b). A new intercomparison (SIRI) is planned for 2013 and includes a set of single tree-ring samples, thus addressing directly some of the IntCal issues.

Publications presenting calibration data sets should include data from relevant intercomparison exercises, present results from other known-age samples, or provide evidence of reproducibility with existing calibration data sets.

### **<sup>14</sup>C Errors and Uncertainties**

The importance of uncertainties relating to counting statistics and those that arise by other means need to be considered separately for each data set and laboratory. However the uncertainties arise, it is crucial to state explicitly what sources have been accounted for and precisely how they have been quantified, and how background and standard errors were derived. The procedures followed in background subtraction and normalization to the standard need to be reported in detail. For clarity, laboratory error multipliers or additional variance should not be included in the reported error but reported separately. A review of the sources of uncertainty in decay counting and accelerator mass spectrometry (AMS) is given below.

#### *Decay Counting Uncertainties*

In traditional decay counting of <sup>14</sup>C (using proportional counters or liquid scintillation), samples were measured to the desired counting statistics and compared with the counting results for a standard and a background (blank). In gas proportional counting, backgrounds and standards were used over a prolonged time (from a few months to a year or so) and measured many times. This resulted in a very low statistical uncertainty in the mean values, which were used by some laboratories in the corrections for all samples analyzed in that period. In other laboratories, the population standard deviation was used, which correctly indicates the uncertainty in background, but overestimates the uncertainty in net standard and sample values when systematic fluctuations, such as seasonality and atmospheric pressure, affected blank, standard, and sample measurements. Likewise for liquid scintillation counting, the backgrounds were generally used for a period of 6 months or so and standards for a year or more. However, for calibration samples, 2 or 3 background and standard vials were measured along with the samples over a period of 2–3 months and generally the mean and uncertainty of those measurements were used for the sample age corrections. As background values were generally high for both methods (several percent of recent count values), subtraction of the (mean) background from the measured sample value resulted (for older samples with small sample activities) in relatively large uncertainties, determined by combination of the sample, standard, and background uncertainties. This is the most basic “raw” error and derives from purely Poisson counting statistics, but it is conventionally modeled as Gaussian distributed in all statistical modeling.

Further uncertainties exist that are, unfortunately, less predictable and do not (typically) obey Poisson statistics. Subtraction of a background measurement corrects for the laboratory contamination in sample pretreatment, combustion, benzene synthesis, etc. The question of whether this specific

blank preparation was representative introduces a further uncertainty. Background corrections to gas counters for atmospheric pressure, season, or slow decay of counter walls likewise are non-Poisson, as are corrections for quenching and cosmic-ray related effects in liquid scintillation. Efficiency and cleanliness of sample preparation chemistry added another non-Poisson variability. The effect of these sources of variability can be quantified from the scatter of many repeated preparations and measurements. Assuming a Gaussian distribution of these could give an effective overall standard deviation to be compared with the Poisson count-derived standard deviation described above and a laboratory error multiplier or additional variance could then be calculated.

#### *AMS Uncertainties*

For AMS measurements, there are some essential differences but also similarities to decay counting. Despite the different physics involved (radiometry versus mass spectrometry), both follow a Poisson distribution (Vogel et al. 2004). Laboratory contamination during sample and target preparation is important for AMS, just as for decay counting. The small sample size allows for an optimal selection of sample material, but makes the result sensitive to even very small amounts of contamination. The other difference lies in the way samples are measured. In each AMS sample wheel or cassette, freshly prepared standard and background targets are measured. Thus, the statistical uncertainty in standard and background is determined within the batch and by how many standards or blanks can be used for the direct comparison with the results of the sample target. On the other hand, the machine background (counts originating from the AMS system itself) is for most systems very low, of the order of 0.2% down to 0.01% of “recent count.” Thus, blank values are mostly determined by contamination inherent to the sample material and its processing. Their variability is non-Poisson and is generally estimated from the population standard deviation of a series of measurements as about one-third of the measured value of the background (independent of, and for older samples much larger than, the statistical counting error). For tightly controlled series, this may drop to one-sixth of the value. Not all AMS laboratories include this empirical, blank uncertainty in their reporting, but this should be considered an essential criterion for calibration data, especially for data sets that are approaching the blank limit.

An additional source of variability in AMS measurements is related to the stability of the AMS system and the homogeneity of the sample target. In some laboratories, this is termed “machine random error” or just “random error” and refers to all sources of error that are not related to counting statistics. If only counting statistics are considered, the reported AMS uncertainty might be (significantly) underestimated. Unless this scatter is accounted for in other ways, the actual variability should be reported. Several AMS laboratories divide the measurement of a target into several intervals and compare the scatter of the interval results (the actual variability) with that predicted for those intervals from counting statistics alone. For homogeneous targets in a stable AMS system, scatter and Poisson statistics agree. If the scatter is significantly larger, it indicates system or target troubles and the larger value should be used. Other laboratories derive an estimate of the machine random error using the total variance minus the variance expected from counting statistics for the suite of standards present in every wheel of targets. Since the standards usually have high  $^{14}\text{C}/^{12}\text{C}$  ratios, the counting statistic uncertainty is usually small and well determined, allowing for a good estimation of the other uncertainty terms using this method. Some of these laboratories use the long-term average of this difference to derive an estimate of machine random error.

#### *Additional Sources of Uncertainty Associated with Correction for Reservoir Effects*

A critical component of uncertainty in any estimate of  $^{14}\text{C}/^{12}\text{C}$  of atmospheric or mixed layer surface ocean derived from corals, forams, and speleothems is that associated with the reservoir age (R) or

dead carbon fraction (DCF), both of which are expected to vary with changing ocean-atmosphere reorganization and associated environmental change. In terms of selection of suitable data, there must be justification for the limited variation in R or DCF and assessment of the offset and uncertainty. Assessing the variation in these parameters is challenging and, currently, the most robust method is to compare data with the tree-ring portion of the calibration curve. While preliminary attempts have been made to assess the variation in R and DCF for individual data sets beyond the IntCal13 tree-ring data by comparison with Suigetsu data (Bronk Ramsey et al. 2012), it is accepted this should be a prime focus for research by the IntCal Working Group prior to future estimates of the calibration curves. For IntCal13, a constant regional value of R was used for each coral or foram data set, but the uncertainty in R used for marine data depends on the calendar age (see Reimer et al. 2013, this issue): For material <13.9 cal kBP, an uncertainty of  $\pm 100$   $^{14}\text{C}$  yr was applied, whereas for older corals  $\pm 200$   $^{14}\text{C}$  yr was used on the basis that R values are likely to be more variable during the last glacial period. It is expected that more scrutiny of reservoir age variability, backed up by modeling evidence (e.g. Butzin et al. 2005; Singarayer et al. 2008; Matsumoto and Yokoyama 2013), will allow for the variation of R in forthcoming work by the IntCal Working Group.

Likewise, speleothems are expected to show variation in DCF as a function of vadose zone hydrology and geochemistry under changing environmental conditions (Hendy 1971; Genty et al. 2001; Fohlmeister et al. 2011; Rudzka et al. 2011; Griffiths et al. 2012). Different samples in the same cave system can have significantly different DCF values dependent on flow paths and drip rates amongst other factors, and they would also be expected to respond to perturbations in a variety of ways, be it dampened, lagged, threshold, or constant. Some of this variation must be accommodated in the DCF-corrected  $^{14}\text{C}$  ages used in construction of the calibration curves, and is considered to be that remaining after subtracting the standard deviation of the mean difference between the  $^{14}\text{C}$  age and IntCal13 tree-ring  $^{14}\text{C}$  age at each calendar age interval. For convenience, this is considered to approximate a normal distribution.

## METHODS

### Timescales and Uncertainties

#### *Dendrochronology*

The use of tree-ring patterns to establish absolute ages was pioneered by A E Douglas working with conifers in the southwest United States and later in central Europe by B Huber on oak (Becker 1992). Since that time, a number of long tree-ring chronologies have been established, including the bristlecone pine chronology (Ferguson 1969; Ferguson and Graybill 1983), which was used to demonstrate the long-term variations in atmospheric  $^{14}\text{C}$  (Suess 1970) and provide essential samples for  $^{14}\text{C}$  measurements used in calibration curves through the 1980s and early 1990s (Klein et al. 1982; Stuiver et al. 1986; Stuiver and Reimer 1993). In Europe, subfossil preserved oak trees from bogs and river gravels were used by different research groups to construct independent long oak chronologies from different regions; those from Ireland (Pilcher et al. 1984) and Germany (Becker and Kromer 1993; Schmidt and Schwabedissen 1982; Leuschner and Delorme 1988; Friedrich et al. 2004) have been used for  $^{14}\text{C}$  calibration. In this way, the European oak chronologies have been independently validated back to 9741 BP (7792 BC) (Pilcher et al. 1984; Spurk et al. 1998). The oldest part of the absolutely dated tree-ring chronology is formed by the southern German oak back to 10,430 BP (8481 BC) and the Holocene oak is extended back to 12,560 BP (10,611 BC) by the Preboreal and Younger Dryas pine chronologies from southern Germany and Switzerland, which

have been linked dendrochronologically to the German oak (Friedrich et al. 1999, 2004; Hua et al. 2009). The Irish oak and German oak and pine chronologies provide the main body of the sample material for the IntCal09 tree-ring-based calibration curve along with trees from the west coast of North America (Reimer et al. 2009). Two independent floating chronologies (Swiss and German) from the late glacial, which have been cross-matched to each other (Hua et al. 2009; Kaiser et al. 2012), have been anchored by a  $^{14}\text{C}$  wiggle-match to these absolute chronologies (Friedrich et al. 2004; Kromer et al. 2004; Schaub et al. 2008) and are included in the IntCal13 calibration curve (Reimer et al. 2013, this issue).

Different tree-ring laboratories have used slightly different methods to test the statistical significance of cross-correlation of a tree-ring series to the master chronology, but Pearson's correlation coefficient combined with a Student's  $t$  test (Baillie et al. 1983) and coefficients of parallel variation (percent of agreement; *Gleichläufigkeit*: GLK) (Huber 1952; Eckstein and Bauch 1969) have been most commonly used. As statistics may provide more than one probable match, the ultimate decision of a cross-match is based on the visual comparison of the series, which relies on the experience of the dendrochronologist. For example, for the construction of the Belfast Irish oak chronology, only matches that were (i) visually acceptable and (ii) produced  $t$  values well in excess of 3.5 were accepted. Even then, a match suggested by the dendrochronologist and not backed up by replicated correlation values would be considered suspect (Baillie 1982; Munro 1984). This conservative approach limited the problems associated with the construction of the long Irish tree-ring chronology. Likewise, for the European late-glacial chronologies the following cross-dating standards have been maintained:  $t$  values  $\geq 4.0$ ; GLK  $\geq 60\%$ ; and an acceptable visual linkage (Kaiser et al. 2012). For the construction of chronologies, critical links, and extensions of existing chronologies, the basal series must be overlapped by  $\geq 100$  rings to avoid random coincidence. The homogeneity and strength of a chronology is best shown using the mean interseries correlation (RBAR) and the expressed population signal (EPS) (Wigley et al. 1984), which give a measure of the common variance of the single series that was incorporated. EPS should exceed the commonly used threshold of 0.85 for the entire length of the chronology for a satisfactory chronology signal. The crucial proof of an absolutely dated dendrochronology is the external validation by significant cross-dating of independently established tree-ring chronologies, as could be shown for the European oak chronologies (Pilcher et al. 1984; Spurk et al. 1998) and for the late-glacial pine chronologies from Switzerland and Germany (Kaiser et al. 2012). Whenever independent chronologies exist, intercomparisons are requested as a crucial and independent validation of the timescales when using the chronologies as a source of  $^{14}\text{C}$  calibration samples. If direct comparisons of ring-width series from different regions are not feasible, because a common signal is not expected,  $^{14}\text{C}$  "wiggle-matching" on series of  $^{14}\text{C}$  data from the chronologies may be an adequate method to compare and verify the timescales (e.g. Linick et al. 1985).

In general, whatever method is used for building chronologies or correlating samples to a master chronology, it is imperative for calibration curve samples that the dendrochronology is well established and fully published. Publication should include details of the methodology used for tree-ring analysis, full details of the cross-matching and cross-dating of each tree-ring series, the remaining uncertainty in the absolute ages, and should cite the version of the chronology used for dating. Raw tree-ring widths of trees sampled for calibration data should be published or logged in a digital archive. Publication of calibration data sets should make clear exactly which rings from which individual tree-ring series were included in each  $^{14}\text{C}$  sample. Whenever possible, pooling of synchronous tree rings of different trees in one  $^{14}\text{C}$  sample should be avoided and samples of single trees should be kept separate.

*Uranium-Thorium Dating*

U-Th dating provides absolute ages for corals and speleothem samples used to construct calibration records. Many of the criteria presented for coral U-Th measurement in Reimer et al. (2002) are applicable to speleothems as well and are summarized below. In general, U-Th age uncertainty is quoted at the  $2\sigma$  level. We note, with caution, that this differs from standard practice in  $^{14}\text{C}$  and Ar-Ar dating and can cause confusion: All data in the IntCal13 database is quoted as  $1\sigma$ . Combined uncertainty includes that associated with all aspects of measurement and derivation, including corrections for analytical blank, decay constants, and internal error. Full documentation of mass-spectrometric protocols should be given, providing details about the calibration of U and Th spikes used to quantify isotopic ratios.

Typically, internal and external reproducibility and accuracy should be demonstrated using standards with well-known isotopic ratios, such as NIST-supplied certified reference materials (112A and 145) for  $^{234}\text{U}/^{238}\text{U}$ . There are no traceable community standards for U-Th ratios and laboratories must rely on in-house standards, perhaps derived from uraninite solutions (e.g. Harwell uraninite) or gravimetrically determined mixed U-Th standards. Also, replicates of different parts of the same sample should be measured as often as possible to derive an estimate of external reproducibility for U-Th ages and  $\delta^{234}\text{U}_{\text{initial}}$ . Durand et al. (2013, this issue) detail efforts to demonstrate consistent results in more than one laboratory.

There have been successful intercomparison efforts among the community involved in PALSEA efforts (Bill Thompson, personal communication). There is strong motivation for more comprehensive comparison, along the lines of the FIRI to VIRI efforts in  $^{14}\text{C}$  (Bryant et al. 2001; Scott 2003; Scott et al. 2010a,b). More widespread intercomparison is likely to follow the imminent distribution of synthetic age solutions among the U-Th community as part of a UK NERC-funded project (“Sharpening the U-Th Chronometer,” 2011–2014) that is based on the U-Pb Earthtime initiative (McLean et al. 2008).

The half-lives used for  $^{238}\text{U}$ ,  $^{234}\text{U}$ , and  $^{230}\text{Th}$  must always be quoted. The half-lives of  $^{234}\text{U}$  and  $^{230}\text{Th}$  were revised by Cheng et al. (2000) and these values were adopted for all U-Th data in IntCal13. New estimates have recently been published by Cheng et al. (2013) with reduced uncertainties and it is likely that there will be amendments in the future.  $^{232}\text{Th}$  concentration of fossil corals should exhibit low values (e.g. less than a few parts per billion) indicating a negligible amount of associated detrital and/or scavenged  $^{230}\text{Th}$ .

Pa-U ages may be useful to check for concordance with U-Th ages measured on samples suspected to be altered by exposure to freshwater (vadose zone and uplifted terraces). However, a systematic survey demonstrating that this criterion allows better screening of corals that remained below sea-water has not been published.

Much of the above applies to U-Th ages derived for calcite from stalagmite, stalactites, and flowstones, but there are additional factors that can affect the overall uncertainty of the calendar age associated with each  $^{14}\text{C}$  age determination in speleothems. Growth rate and sample size is important. In contrast to corals, where sufficient material can be obtained from subannual bands, many years of growth are sampled in speleothems to provide sufficient material for analysis. The morphology and growth rate of a sample must be taken in to account if the associated  $^{14}\text{C}$  determination is not analyzed on exactly the same subsample or interpolation is involved (see section “Age-Depth Models”). With increasing precision and smaller sample sizes, it has been noted that in some settings there can be elevated concentrations of initial  $^{230}\text{Th}$  in speleothems. The initial  $^{230}\text{Th}/^{232}\text{Th}$

ratio should be assessed routinely and, if values significantly different from Bulk Earth values are apparent for individual growth layers, one would expect to see an estimation of within sample variability (e.g. Beck et al. 2001; Carolin et al. 2013). Where  $^{232}\text{Th}$  concentrations are very low, corrections are negligible, but it is expected that some assessment of potential variation of initial  $^{230}\text{Th}/^{232}\text{Th}$  ratio is made by isochron analysis (Richards and Dorale 2003).

#### *Varve Counting*

Sedimentation in any lacustrine or marine archive is sensitive to changes in the prevailing conditions. This is true on all timescales, from individual events lasting days through to millennial length changes in climate. Where the seasonal signal is strong enough, it is possible for varves to form by a number of different processes (clastic, biogenic, chemical). Their survival in the sediment record is normally prevented by bioturbation or other disturbances and as a result they usually only form in anoxic and sheltered conditions. These varves then provide us with a method for relative dating entirely analogous to ice-core layers or tree rings (Lamoureux 2001; Zolitschka 2003; Brauer 2004; Ojala et al. 2012).

Although varves have the potential to provide timescales for calibration purposes, there are a number of issues that need to be considered when using them. The most obvious is that varves are only a relative dating technique, and rarely extend right up to the present in archives that might be used for calibration. It is therefore essential that varved archives used for  $^{14}\text{C}$  dating are linked in some way to another chronology which itself fulfils the requirements for calibration (typically dendrochronology or U-Th dating). More difficult to deal with is the fact that varves are rarely truly reliable chronometers; there is almost always some ambiguity when assessing the annual cycle and both missing varves and double counting of years due to extreme events are possible problems. For this reason, 3 criteria must be met in the application of varved chronologies: firstly, the varves must be studied, at least in part, by thin section in order to understand their nature and to check for possible changes in sedimentation such as hiatuses and event layers; secondly, the varves should be counted by more than one person (Ojala et al. 2012) and ideally by more than one method; finally, some assessment of the uncertainty in the varve count should be made, both in terms of relative errors and cumulative uncertainty.

In practice, cumulative uncertainties in varve chronologies may be on the order of 1–2% (Hughen et al. 1998) but increase for the older portion of very long records such as Lake Suigetsu (Bronk Ramsey et al. 2012). For this reason, it will usually be necessary, not only to have a single tie-point for such a chronology but also constraints from, or checks against, other chronologies (which fit the calibration criteria) to check for long-term drift and identify any significant anomalies that might not be apparent in the sediment itself. Control points to other chronologies should ideally be based on physical mechanisms that provide true synchrony (such as tephra or cosmogenic isotope signals). Where climatic correlations are used, the basis for assuming synchrony and the uncertainties in such synchrony need to be made clear.

#### *Wiggle-Matching*

Wiggle-matching is used to anchor a “floating” (relative) chronology with known spacing between determinations to another record for which an absolute chronology is available. A floating sequence of  $^{14}\text{C}$  determinations is typically anchored by matching the  $^{14}\text{C}$  variations in the floating record to those in one that already has an independently derived absolute chronology. This can be done either using a classical best-fit approach (Pearson 1986) or a Bayesian method (Christen and Litton 1995; Bronk Ramsey et al. 2001). The uncertainty induced by undertaking the wiggle-match is shared by

all of the data points in the floating sequence and thus must carefully be articulated so that the dependence that is induced between them can be properly accounted for in comparisons with other data sets. This uncertainty must be recorded separately from any other sources of error affecting those points.

#### *Age-Depth Models*

For some archives, such as speleothems, the sampling intervals for <sup>14</sup>C age and calendar age measurements may be at different depths within the sequence. This results in the need for an age-depth model to provide the necessary chronological information at the depths where the <sup>14</sup>C measurements were made. Any age-depth model should be implemented in such a way that the data providers can offer not just a statement of the most likely chronology, but can clearly articulate the nature, scale, and structure of all associated uncertainties. Typically, such modeling will induce dependence between the errors on different ages; in such cases, the matrix of covariances between them (or sufficient information to reconstruct it) should be made available.

#### *Tie-Pointed Timescales (“Tuning”)*

Tie-pointed timescales are based on the following assumptions:

1. The climate proxies in both the independently dated master record and the data set to be tie-pointed to it record the same events with approximately the same relative magnitudes. In some cases, a particular series of climatic events may be recognized, such as interstadials in which a strong signal precedes 3 small signals (e.g. Bond et al. 1993);
2. Key climatic events, such as abrupt (decadal) transitions into stadials and interstadials, are recorded in both the master and “tuned” records within a known or estimated lead or lag. This may need to be established with independent evidence (e.g. tephra layers within Younger Dryas sediments) or from a different period with independent chronologies (e.g. varved sediments in the Cariaco Basin during the deglaciation but not during earlier stadial events; Hughen et al. 1996, 2004).

If such assumptions hold, then suitable climatic changes and events should be recognizable in all targeted ice cores, speleothems, and marine records with sufficient resolution and preferably multiple proxy measurements.

It is essential that the paleoclimatological or paleoceanographical signal of the proxies’ response to climate changes is thoroughly understood and documented (i.e. in refereed publications). The reasons for assuming synchronicity, including any leads or lags, and a solid assertion of the physical mechanism allowing the climatic signal to be expressed in both the master and tuned record must be published in an international, peer-reviewed journal. It must be clear which master climate record and timescale were used and also how tie-points were selected and ages between tie-points were modeled. The relationship between climate and growth/accumulation rate should be taken into account, and suitable tie-points selected to avoid artifacts from accumulation rate changes. We recommend that several different proxies are measured in the archive being tuned in order to check correlation with the master record (cf. Bard et al. 2004, 2013, this issue). As with speleothem age-depth models, the uncertainty of a calendar age in the tie-pointed record is not independent. A covariance matrix to fully account for this dependency should be provided (cf. Heaton et al. 2013, this issue).

### Data and Metadata Requirements

Every calibration data set should include the metadata (Table 1) and sample-specific information (Table 2). Additionally, a covariance matrix may be attached to the data record (see section “Tie-Pointed Timescales”).

Table 1 Metadata requirements for the IntCal database.

Metadata name	Example
Location of archive	Lat/Lon, name of location
Method of $^{14}\text{C}$ measurement	LSC, GPS, or AMS
Archive code or name (e.g. core ID, tree name)	e.g. PL07-58PC
Laboratory uncertainties reported in $^{14}\text{C}$ error fields in the data table (note that any laboratory error multiplier or extra additive error should be reported separately from the basic measurement error)	Long-term background variability (e.g. sigma background = 1/3 measured background), long-term standard variability, lab error multiplier, and/or extra additive error
Detailed sample preparation and pretreatment prior to $^{14}\text{C}$ measurement	Physical: e.g. powdered, ground, or taken as a slice or wafer chemical: e.g. alpha-cellulose, ABA, acid-etched (leaching), drying and operating temperature, preservation conditions, acid/alkali concentration, solvent mixture, inert atmosphere, with references if appropriate
Detailed sample preparation and pretreatment prior to cal age measurement and estimation	
Methods used to estimate cal age uncertainties reported in the data table	

Table 2 Data requirements for the IntCal database.

Data item name	Example
$^{14}\text{C}$ laboratory ID	e.g. QL-12164
cal age BP	
cal age span	Number of tree rings in sample, etc.
Dependent cal age uncertainty	Wiggle-match uncertainty
Independent cal age uncertainty	Uranium-thorium uncertainty
Cumulative cal age uncertainty	Cumulative varve count uncertainty
$^{14}\text{C}$ age BP	
$^{14}\text{C}$ error (1 s.d.)	Reported measurement error including errors in blanks, standards
$^{14}\text{C}$ error multiplier, if applicable (a positive value to be used to scale the reported measurement error, typically on a collection of related samples, via multiplication)	Derived from replicate analysis of samples or secondary standards or comparison to existing data (such as done for tree rings in IntCal04, IntCal09)
$^{14}\text{C}$ additive error, if applicable (a positive value to be used to increase the reported uncertainty via addition in quadrature)	Additional uncertainty not included in an error multiplier (e.g. sample processing uncertainty)
Reservoir offset	Marine reservoir age offset or dead carbon fraction offset in speleothems
Reservoir offset uncertainty	Estimate of uncertainty in the reservoir offset



## DISCUSSION AND CONCLUSION

In summary, steps should be taken at every stage of sample selection, pretreatment, and measurement to ensure transparency for the generation of high-quality data sets (including careful articulation and quantification of uncertainties). The quantification and classification of errors in both the  $^{14}\text{C}$  and the absolute timescale are of utmost importance. This article outlines a range of archives that may provide useful data sets for  $^{14}\text{C}$  calibration. All of these have strengths and limitations, and we propose criteria relevant to each record that we believe will maximize its utility for accurate  $^{14}\text{C}$  calibration. Science is, however, never static and, just as calibration curves are always works in progress, so must be the criteria for the inclusion of data sets in any “consensus”  $^{14}\text{C}$  calibration curves. Beneath the detailed criteria proposed for each archive are common principles; that data should be published in as much detail as possible and that all sources of uncertainty should be explored as rigorously as possible. Calibration data have a wide significance and application beyond the discipline and the time in which they were created. It is essential that these data sets are published in sufficient detail to allow future generations of researchers to re-examine them in the light of new scientific understanding as this emerges.

With this in mind, we invite colleagues who have data sets that they feel meet the criteria outlined in this paper to contact a member of the IWG with a view to their inclusion in the next update of the IntCal curves. We also invite comments and suggestions on how the criteria outlined in this paper, and the calibration curves based on them, might be improved.

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