10. ^{14}C CHRONOSTRATIGRAPHIC TECHNIQUES IN PALEOLIMNOLOGY

SVANTE BJÖRCK
(svante.bjorck@geol.lu.se, svante@geo.geol.ku.dk)
Department of Quaternary Geology
Lund University, Tornavägen 13
SE-223 63 Lund, Sweden

Geological Institute
University of Copenhagen
Øster Voldgade 10
DK-1350 Copenhagen K
Denmark

BARBARA WOHLFARTH (Barbara.Wohlfarth@geol.lu.se)
Geological Institute
University of Copenhagen
Øster Voldgade 10
DK-1350 Copenhagen K
Denmark

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Introduction

Down-core paleolimnological investigations of lake-sediment sequences require sufficient age control to enable comparisons and correlations on local, regional and global scales. Provided that the sediments are annually laminated, age control may be achieved through counting of annual layers or varves (see Lamoureaux, this volume). However, since only sediments deposited under certain conditions will allow obtaining an annual time resolution, other dating techniques based on, for example, the radioactive decay of certain elements will have to be applied. Among these, radiocarbon dating (^{14}C) is the most widely used and also the earliest radiometric method available. The method was 'invented' in 1951 by Libby (1955), who subsequently introduced and applied it to date the recent geological past. The background and principles of radiocarbon dating have been outlined and discussed in detail in numerous textbooks, journals and articles (see e.g., Lowe & Walker, 1997; Lowe, 1991a;

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Smart & Frances, 1991; Olsson, 1991; 1986), as well as in specific volumes of the journal *Radiocarbon* and will, therefore, only shortly be summarised here.

^{14}C atoms are continuously produced in the upper atmosphere, where cosmic ray flux leads to the collision of free neutrons with other atoms and molecules. One of the effects of these nuclear reactions is the displacement of protons from nitrogen atoms (^{14}N) to produce carbon atoms (^{14}C). The radioactive ^{14}C isotope survives on average for 8270 years before decaying into the stable element ^{14}N. ^{14}C atoms are rapidly oxidised to carbon dioxide ($^{14}CO_2$), become mixed throughout the atmosphere, and absorbed by oceans and by living organisms during tissue building. During the lifetime of an organism, the carbon used for tissue building will be in isotopic equilibrium with its contemporaneous life-medium (atmosphere, ocean or fresh-water). Upon death, uptake of CO_2 stops, while the decay of ^{14}C in the organic tissues continues. Radiocarbon measurements of fossil organic matter are based on this decay process and allow, together with the internationally agreed fixed half-life of the ^{14}C isotope of 5568 years (Mook, 1986), to determine the age of the fossil material. However, because of the relatively short half-life of the isotope, radiocarbon dating can only be applied back to c. 40,000 years. In addition, due to the fairly large measuring uncertainties, varying atmospheric ^{14}C content, combustion of fossil fuels (producing "old" CO_2) and nuclear weapon tests (increased ^{14}C production), the technique can hardly be used for the last few hundred years. For such young sediments, measurements of the short-lived ^{210}Pb and ^{137}Cs radioisotopes (see Appleby, this volume) can complement the ^{14}C method.

Although the three carbon isotopes ^{12}C, ^{13}C, and ^{14}C have natural occurrence ratios, a fractionation of these ratios often occurs in nature. These effects are fairly small, but they can significantly influence radiocarbon ages where the precision is less than 1%. Therefore the $^{13}C/^{12}C$ ratio is measured and compared with a limestone standard, PDB, which consists of belemnites from the so-called Peedee formation in South Carolina (Craig, 1957), and most terrestrial/lacustrine samples have negative values compared to this standard. During calculation of the ^{14}C age, the ^{14}C activity is normalised in relation to a $\delta\,^{13}C$ value of -25%, the value for wood. For example, a 5% depletion ($\delta^{13}C = -30\%$) in the $^{13}C/^{12}C$ ratio implies a 10% depletion in the $^{14}C/^{12}C$ ratio, which means that the ^{14}C activity should be increased by 10% of the mean lifetime of ^{14}C (8270 years), equivalent to 83 years (Harkness, 1979). Furthermore, all radiocarbon dates are reported with a statistical uncertainty of one-standard deviation, mainly related to uncertainties of measurements and background radiation. If an age is reported as 3560 ± 120 ^{14}C years BP, it means that the 68% confidence interval for the age of this sample ranges at between 3440–3680 ^{14}C BP, while the 95% confidence interval is between 3320–3800 ^{14}C BP.

Lake sediments usually contain a certain amount of organic carbon in the form of terrestrial, telmatic and limnic plant and animal debris and are therefore highly suitable for radiocarbon dating. Since the discovery of the radiocarbon dating method c. 50 years ago, radiocarbon measurements have been performed on numerous lake-sediment sequences in different geographic settings and on all continents, and with a variety of scientific objectives. The majority of these investigations are aimed at obtaining a general age control for the studied sequences by dating selected parts, and only relatively few studies have been directed at recovering very dense sets of ^{14}C dates along the whole sediment column. The scarcity of such high-resolution dated sequences is due to different reasons. The research budget may not have allowed covering the costs for dense ^{14}C dating series or the focus of the study was directed at a specific aim (e.g., dating the onset of sedimentation in a lake basin, its isolation from the sea, or a short, and for some reason more interesting time interval, or a specific event in the lake's history); or, only a rough age estimate was considered necessary, which may be carried out by interpolation between a few dated horizons.

However, the increased demand on studies with good time resolution (e.g., Lowe, 1991b), has led to fewer but more chronologically focussed investigations. Together with the now frequently-used accelerator mass spectrometry (AMS) ^{14}C dating method, this has produced some extremely well-dated limnic sequences, but has also brought attention to many pitfalls connected with the usage and interpretation of both single and large sets of ^{14}C dates performed on various types of materials.

For many years, but no longer, the journal *Radiocarbon* published all radiocarbon dates obtained at different radiocarbon laboratories. It also publishes articles connected to all aspects of radiocarbon dating (e.g., technique developments, dating for archaeology, calibration, ^{14}C in marine, lacustrine and soil systems), and is thus probably the best source of information for radiocarbon related issues.

Methods and problems

Conventional versus AMS ^{14}C *dating*

Two different approaches for radiocarbon dating fossil material are now available. The original method, the so-called 'conventional radiocarbon dating technique' is based on decay counting of the isotope, while the fairly new accelerator mass spectrometry (AMS) technique is based on particle counting. Detailed descriptions of the individual approaches and techniques have been extensively described in the journal *Radiocarbon* and in various textbooks (Lowe & Walker, 1997). The AMS ^{14}C method, which has been developed and improved over the past 10–20 years, has partly revolutionised radiocarbon dating, because only small amounts of pure carbon are needed to perform a measurement (Linnick et al., 1989).

Before AMS ^{14}C dating became available, radiocarbon measurements were entirely based on decay counting, i.e., on the 'conventional' technique. For such measurements 0.5–1 g of pure carbon is required (Fig. 1), which means that, in the case of samples with low organic content, fairly large samples are necessary to obtain a ^{14}C age. Consequently, unless peat, charcoal, large plant/animal fragments or concentrated layers of macrofossils (e.g., moss-rich horizons) could be dated, bulk sediment samples had to be used. Such samples often comprised intervals of 2–10 cm. The resulting chronology was often characterised by a low depth/time resolution and in the case of low organic content, also by fairly large standard errors unless large enough samples were submitted for dating. However, in the case of organic-rich deposits, many attempts were made to overcome this problem by dating very thin sediment slices, and thereby reducing the error within samples. Furthermore, the conventional technique can be more precise if enough carbon is at hand, which is shown by, for example, the large sets of such high precision dates on tree rings.

A major step forward was achieved with the implementation of the AMS ^{14}C technique (Fig. 1). The possibility of not only dating very small amounts of sediment material, but also different parts of the sediment (i.e., identified organic material), has reduced many of the errors/uncertainties connected with the conventional dating method. Consequently,

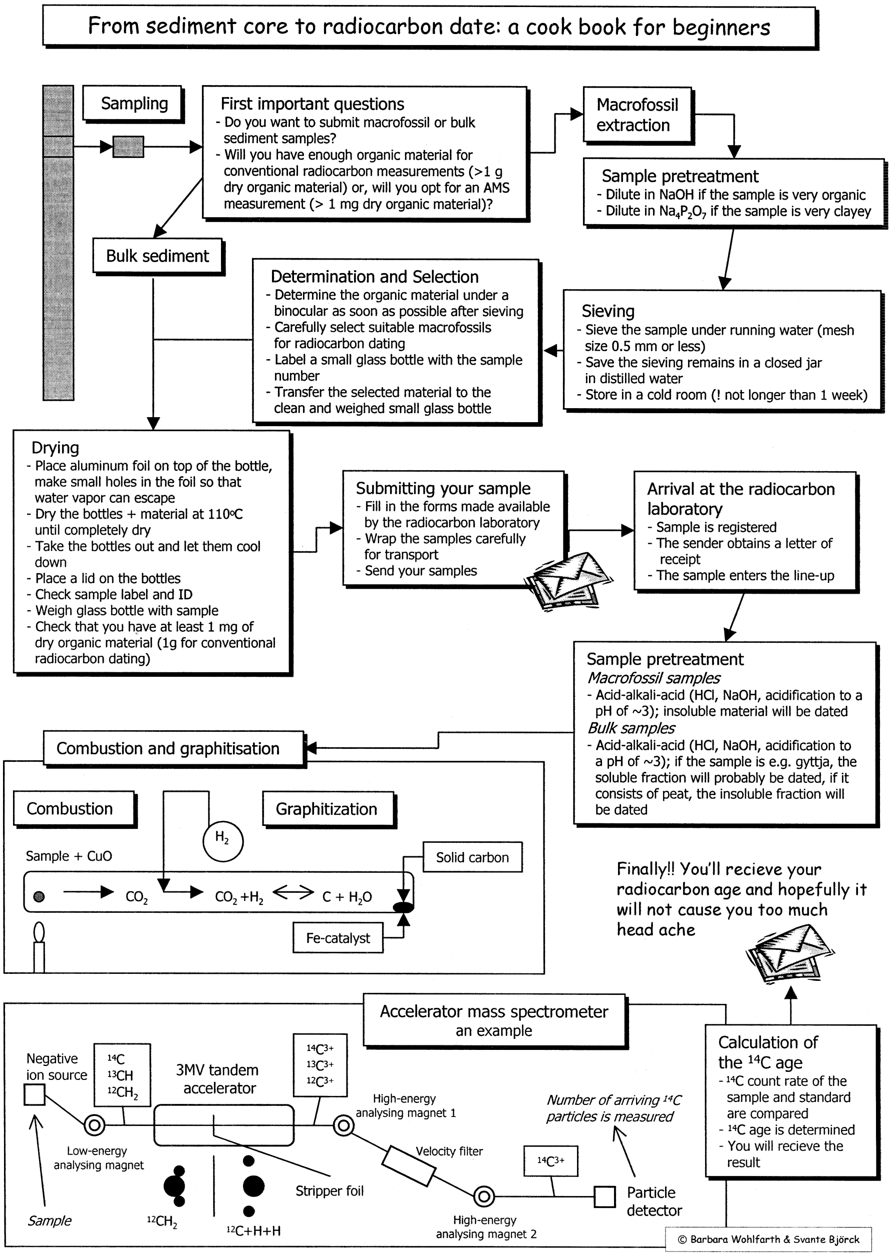

Figure 1. Sketch, illustration the long way from sediment sample to radiocarbon date. The extraction of plant macrofossils from sediment samples and their preparation is according to the technique employed at the Department of Quaternary Geology, Lund University. The shown schematic pictures, which exemplify the combustion/graphitisation process and one type of accelerator mass spectrometer is based upon the techniques used at the Lund University AMS facility.

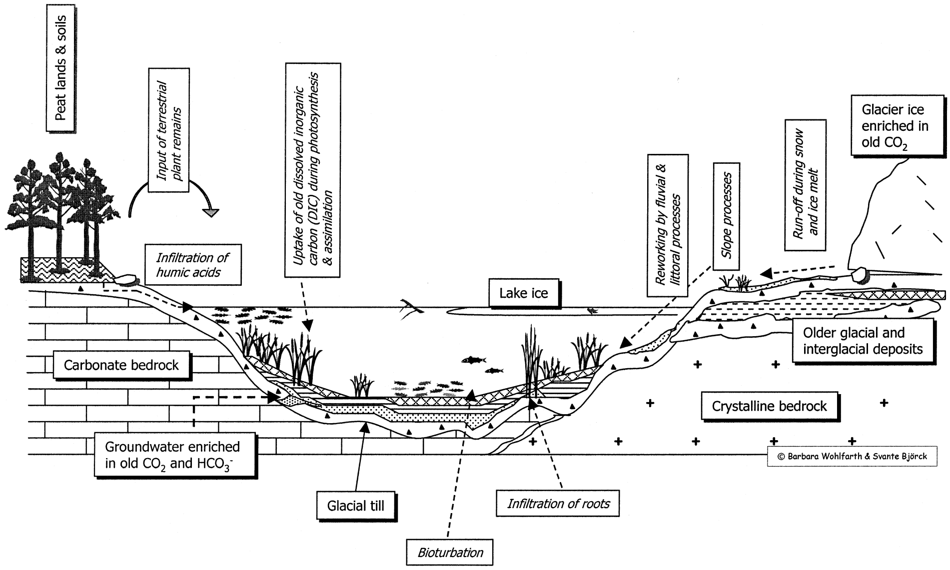

Figure 2. Sketch showing a variety of possible sources of errors, which can influence bulk sediment radiocarbon dates in a hard-water and a soft-water lake, and which are further discussed and exemplified in the text. Although the main difference between the two lake types is related to the carbonate availability from the substratum (carbonate-rich sedimentary rocks and/or sediments vs. non-carbonate bedrock and/or sediments), several other factors may affect the composition of sediments and lake water in both types of lakes. Such are, for example, contamination by old and young organic material (reworking and deposition of older organic deposits, infiltration of humic acids, root penetration, bioturbation), perennial lake ice cover and/or inflow of glacial melt water (enrichment of the lake water by old CO_2). The lake may also be fed by groundwater containing old dissolved inorganic carbon (DIC) or, in volcanic areas the lake water may be enriched in old CO_2 from volcanic emissions. While these latter processes are more obvious in a soft-water lake, they are 'hidden' in hard-water lakes.

AMS measurements can result in a much better time resolution of the individual samples and of the sediment sequence as a whole, and lead to a better understanding of the problems connected with dating bulk sediments. However, its application has also shown that a careful treatment of the individual samples, often consisting of identified macrofossils, is necessary to obtain reliable ages (Fig. 1).

Sources of error

Lake sediments reflect a variety of different deposits ranging on a scale from purely allochthonous to purely autochthonous, minerogenic and/or organic material. They may contain, for example, precipitated and/or in-washed minerogenic matter, terrestrial and aquatic plant and animal remains, including algae, bacteria, fungi, as well as reworked older organic material (Fig. 2). The organic material may also be affected by diagenesis.

Although careful pre-treatments (Fig. 1) are applied to all samples before a radiocarbon measurement (see e.g., Lowe & Walker, 1997), a large number of unknown factors will still influence the resulting radiocarbon age, especially if it has been obtained on the bulk sediment. If only single dates are obtained along a sediment sequence, the likelihood and amount of contamination will, therefore, be difficult to appraise.

Lake water composition is one major limiting factor for obtaining accurate radiocarbon ages on bulk sediment and aquatic plant and animal samples (Olsson, 1991, 1986). A second important factor is contamination by younger carbon through root penetration (Kaland et al., 1984), by percolating younger humic acids, or by downward movement through bioturbation. Bulk sediment samples may also have been contaminated by minerogenic carbon containing "dead" ^{14}C (Fig. 2), such as coal, graphite and chalk (Lowe, 1991b; Olsson, 1968). A further source of error is related to sample storage and sample size (Wohlfarth et al., 1998b; Hedges, 1991; Olsson, 1991; 1979; Geyh et al., 1974). When a sample is submitted for radiocarbon dating (Fig. 1), it is, therefore, very important to know as much as possible about the depositional environment and the post-depositional processes, which may have affected the sample. Furthermore, detailed information on composition, treatment, storage and size of the submitted material usually has to be reported to the radiocarbon laboratory together with the sample (Fig. 1).

A commonly neglected source of error is that ^{14}C dates are often published with 1-sigma (σ) errors. Attempts are then made to fit a best depth-age curve through as many as possible of the reported, or calibrated, ages (with one standard deviation), although statistics tell us that out of a series of, for example 15 dates, only 10 of them should be on the curve. That this is a "forgotten fact" has become more obvious with the increased number of high-resolution studies resulting in highly variable sedimentation rates when the depth-age curve is fitted to as many ^{14}C dates as possible. The other extreme case is the perfectly smoothed curve, often based on some kind of mathematical function fitted to the dates, which leaves out any possibility for sudden sedimentary changes. Such curves may be useful in low-resolution studies of a homogenous sediment sequence, but should be avoided in detailed chronologic studies, since gradual but important changes in sediment focussing may hardly be discernable in the lithologic record but only from detailed dating series. On the other hand, if clear changes in the sediment lithology are observed, a "golden rule" is to try to fit any probable change in sedimentation rate, implied by the (calibrated) datings, to the observed lithologic changes.

Contamination by old and young organic material

An important source of error in lake sediments is related to input of reworked material into the sediments by a variety of natural processes in and around the lake (Fig. 2). This type of contamination thus consists of organic material, which is older than the age of the final sediment deposition. It may, for example, contain older Quaternary organic material (Björck & Håkansson, 1982; O'Sullivan et al., 1973) or pre-Quaternary coal, graphite or lignite particles in the sediments (Wohlfarth et al., 1995b; Björck et al., 1994; Olsson, 1968).

During studies of dating emergence of lake basins (so-called isolations) in the Baltic Ice Lake (Björck, 1979), it was found that datings of organic-poor sediments deposited just prior to the lakes' isolation yielded ^{14}C ages several thousand years older than the datings performed on the more organic-rich sediments from the lowermost post-isolation level. One possible reason for these age anomalies was prescribed to a larger ratio of reworked organic material in the Baltic Ice Lake clays and gyttja clays (Björck, 1979). This suspicion was confirmed by a more systematic study by Björck & Håkansson (1982), who found that the dating error of late-glacial gyttja clays/clay gyttjas is closely related to the amount of re-deposited pollen grains and inversely related to the percentage of organic carbon. Thus radiocarbon dates on sediments not too poor in organic carbon ($>$ 3–5%), and with a constant, but small amount of supposedly reworked pollen grains ($<$ 1%), yielded negligible dating errors. However sediments, which consisted of a larger portion of reworked grains (i.e., allochthonous organic material), were more subject to dating errors. This was especially true if the sediment contained little organic carbon ($<$ 2%), which is often the case with deglacial/late-glacial sediments. To avoid these problems, Björck (1984) extracted large amounts of aquatic mosses from multiple parallel cores by sieving thin clay gyttja horizons rich in mosses. In this way, a high-resolution chronology for the Older Dryas cold period was achieved with the conventional (decay) method. The resulting age turned out to be very similar to the official, and bulk sediment based age of the Older Dryas Chronozone (Mangerud et al., 1974).

However, later studies have been performed to compare radiocarbon measurements on terrestrial macrofossils, i.e., on plants known to incorporate atmospheric CO_2, with those obtained on contemporaneous soft-water bulk sediments. For example, Björck et al. (1998a) could show that late-glacial, soft-water, bulk sediment ages are often at least 200 years, and in some cases up to perhaps 600 years older than the corresponding ages on plant macrofossils (Fig. 3), although organic carbon values are as high as 5–9%. In fact, the results implied that periods of climate change, in spite of increased organic matter, correspond to levels with the largest differences. This was attributed to increased soil erosion and thereby input of reworked, older organic material. Furthermore, the detailed study by Barnekow et al. (1998), who performed AMS ^{14}C dates on more or less carbonate-free bulk sediments (containing c. 20% organic carbon) and on terrestrial plant macrofossils at the same levels along an almost entire Holocene sequence, is a warning example of dating even Holocene, organic-rich, bulk sediments (Fig. 4). The study illustrates a distinct offset and also variability along the sediment core, but the reason is not clear-cut. It may either be due to the presence of reworked old organic material in the sediment, as discussed above, or caused by a lake reservoir effect. In spite of the absence of carbonates in the sediments, the fairly high pH of 7.5–8 in the lake water (Barnekow et al., 1998), shows that it is a hard-water lake and that the dates may suffer from a subtle hard-water reservoir effect (see below).

There can, however, be exceptions to the more or less unspoken rule of preferably dating macro remains from plants and animals in soft-water lakes, or plants utilizing atmospheric CO_2 in hard-water lakes. Some AMS ^{14}C dating series on bulk sediments, complemented by macrofossil dates and well-dated tephras from the Faeroe Islands (Fig. 17) and Iceland, have shown that these often extremely soft-water lakes seem to yield as reliable ages as the macrofossil dates (Björck et al. in prep.). The reason for this anomaly may be that diamicts and glacial sediments in these more northern, less forest covered areas are much poorer in reworked interglacial organic material than what seems to be the case in more southern glaciated regions. For example, Danish glacial tills and clays have been shown to be fairly rich in pollen grains and other reworked microfossils (Iversen, 1936). Similarly, the results by Gulliksen et al. (1998), who performed comparative AMS radiocarbon dates on terrestrial plant macrofossils and on the NaOH-soluble fraction of gyttja on the sediment sequence from Kråkenäs, Norway, show perfect agreement between the two sets. This may also be a good empirical argument for using the NaOH-soluble fraction for sediment dates.

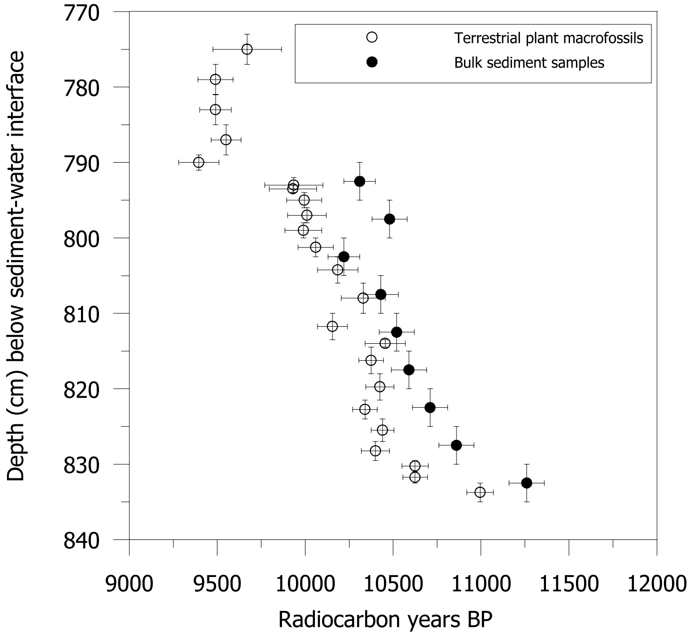

Figure 3. Comparison of results from conventional ^{14}C measurements on bulk sediment samples (filled circles) and AMS ^{14}C measurements on terrestrial plant macrofossil material (open circles) at the site Madtjärn in southwestern Sweden (Björck & Digerfeldt, 1991; Björck et al., 1998a). All measurements are displayed with one standard error. For the bulk sediment samples, which were measured earlier with the conventional technique, much more sediment material was needed (Björck & Digerfeldt, 1991), shown by the large vertical bars, compared to the later AMS ^{14}C dated plant macrofossils (Björck et al., 1998a).

In fact, many of the erroneous/questionable sediment dates reported over the years do not seem to have been carried out on the NaOH-soluble fraction, but rather on the whole bulk sediment.

Therefore, to overcome some of the problems mentioned above, it has often been recommended (e.g., Olsson, 1986) to preferably date the NaOH-soluble fraction (mainly humus) in bulk sediments (see more below) to avoid dating the more insoluble old carbon, which is possibly one main reason for too old ages in organic-poor sediments. This procedure is in contrast to the usual procedure of dating the NaOH-insoluble fraction on macrofossils to ensure dating the original organic material.

In arctic oligotrophic lakes from Baffin Island it has been suggested that ^{14}C depleted particulate and dissolved organic carbon (POC and DOC), transported from soils and peat in the watershed of the lakes, may have a large influence on the age of the surface sediments (Abbott & Stafford, 1996). The ^{14}C age of the sediment-water interface was dated to c. 1000 years BP in three different lakes, while the age of soils and peat varied between 1600–5400 years BP, and the turnover time for organic matter in soil profiles of the watershed was $>$ 2000 years. In such extreme environments, with lakes of low aquatic production, the allochthonous organic fraction may make up a large part of the total organic matter,

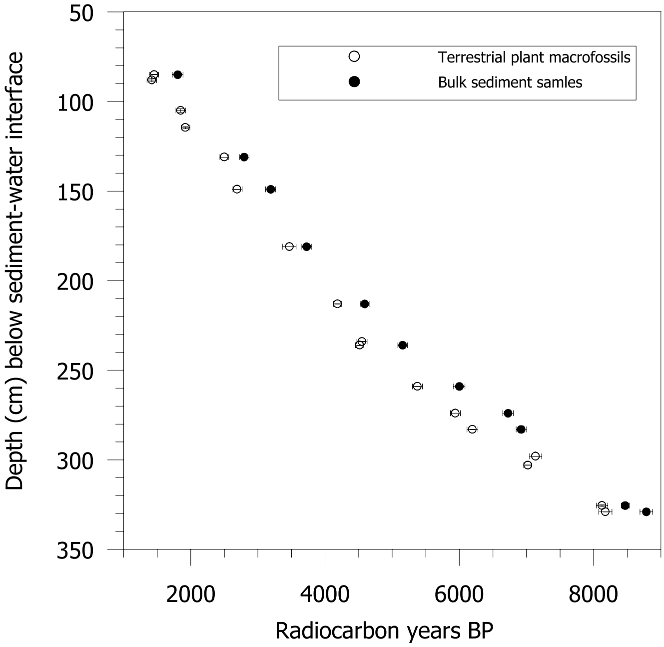

Figure 4. Comparative AMS ^{14}C measurements on bulk sediment and terrestrial plant macrofossils from Lake Vuolep Njakajaure, northern Sweden after Barnekow et al. (1998). The terrestrial plant macrofossil samples comprised fruits, twigs, catskin scales, budscales and leaves of *Betula nana* and *B. pubescens*, leaves of *Salix* sp., fruits of *Alnus incana* and needles of *Pinus sylvestris*. The off set between bulk sediment and terrestrial dates varies considerably (800–300 ^{14}C years), but shows a decreasing tendency upwards in the sequence. According to Barnekow et al. (1998), the bulk organic material in Lake Vuolep Njakajaure, which has a carbonate content of $<$ 2–3% and an organic content of 40–50%, consists mainly of algae, the pH of the lake varies between 7.5–8, water depth is 14 m and bottom waters are characterised by oxygen deficiency. The closest outcrop of carbonate bedrock is situated c. 2 km from the lake, but the Quaternary glacial deposits around the lake may contain carbonates.

and may thus influence the composition of the sediments. If the allochthonous fraction consists of old organic matter, washed out from peats and soils, it will obviously increase the age of the sediment. Such considerations may be very important for paleolimnologic studies of lakes with low productivity surrounded by a landscape rich in peatlands and thick soils.

Contamination of a sediment sample by younger carbon (Fig. 2) may either arise from roots penetrating into the sediments, from infiltration by younger humic acids or through bioturbation (Olsson, 1991). A study by Kaland et al. (1984) showed that *Isoëtes* roots, which penetrate far down into older sediments, can substantially influence the age of bulk sediment samples. Bulk radiocarbon dates on clayey sediments underlying peat also displayed ages several hundred years younger than expected (Hedenström & Risberg, 1999; Åkerlund et al., 1995) and the errors are explained by contamination through either rootlets or humic acids, which percolated down into the sediment. Bacterial action within sediments has generally little effect on radiocarbon measurements, because the carbon atoms are recycled (Hedges, 1991). However, if this recycling involves transport of metabolites in the sediment column, it will result in a type of “molecular bioturbatio” (Hedges, 1991).

General lake reservoir effects

If the $^{14}C/^{12}C$ ratio of the carbon, from which the aquatic plants built up their tissue was lower than the $^{14}C/^{12}C$ ratio in the CO_2 of the contemporaneous atmosphere, the dating of such plant material is regarded to have been affected by the so-called “lake reservoir effect”.

Radiocarbon measurements on bulk sediment samples from soft-water lakes have generally been regarded as giving fairly accurate dates. Less attention has, therefore, been placed on likely errors connected with such samples, although Olsson (1986) and Sutherland (1980) have highlighted these problems already many years ago. An age gradient between soft lake water and the atmosphere can be explained in different ways. It may either be related to the fact that the lake has been efficiently sealed off from the atmosphere by lake ice, that the lake is mainly fed by water from a glacier containing old CO_2, or that “old” groundwater completely “contaminates” the age of the lake water. However, volcanic activity may also contribute to an increased age of the lake water by input of older CO_2 (Hajdas, 1993; Sveinbjörnsdóttir, 1992; Olsson, 1986).

During studies of Antarctic lakes around the Antarctic Peninsula (Björck et al., 1996b; 1993; 1991b; 1991a; 1991c; Zale, 1994; Björck & Zale, pers. comm.), in the Vestfold Hills (Bird et al., 1991), and in the McMurdo Dry Valleys (Doran et al., 1999; 1994; Squyres et al., 1991), major dating problems have been encountered, mainly related to reservoir effects. Some of these studies can be used as examples, although extreme, for these effects. They are mainly caused by the influence of glacial melt-water, containing old CO_2, and the insufficient equilibration between the lake carbon reservoir and atmospheric CO_2. The influence of the former effect is related to how well the “old” glacial melt-water is mixed with atmospheric CO_2. One test by Doran et al. (1999) showed that 7500- year old dissolved inorganic carbon (DIC) of glacier ice was modernized to 600 years in a near-by pool, and the melt-water was completely equalized with modern $^{14}CO_2$ when it reached a lake 3 km downstream.

The second effect is related to the perennial ice cover, which seals off the lake water from the atmosphere, often in combination with influences from glacial melt-water. The age of DIC of the surface water in two of the Dry Valleys lakes (Lake Hoare and Lake Bonney) varies between 1600–2000 years, while DIC of the bottom water has ages of 2700 and 10,000 years BP, respectively, without reducing for the surface reservoir (Doran et al., 1999). Furthermore, ^{14}C dates of microbial mats in a sediment core from Lake Hoare suggest a reservoir age of 2600 years for the surface sediments, which thus fits well with the age of DIC of the bottom waters.

The extreme ^{14}C results from some of the lake studies from Antarctica can thus explain some of the more subtle dating anomalies in less extreme environments. For example, the paleolimnological studies around the Antarctic Peninsula have shown that radiocarbon dates on aquatic mosses from soft-water lakes in this region can generally be regarded as fairly reliable. Their validity could be confirmed by dates obtained on terrestrial mosses and through tephra correlations. In fact, most of the other dated components of the Antarctic Peninsula lake sediments — whole bulk samples, the NaOH-soluble fraction, and the NaOH-insoluble fraction — resulted in highly variable and considerably higher ages than the moss dates (Björck et al., 1991b). The reason for these anomalies is not clear, but

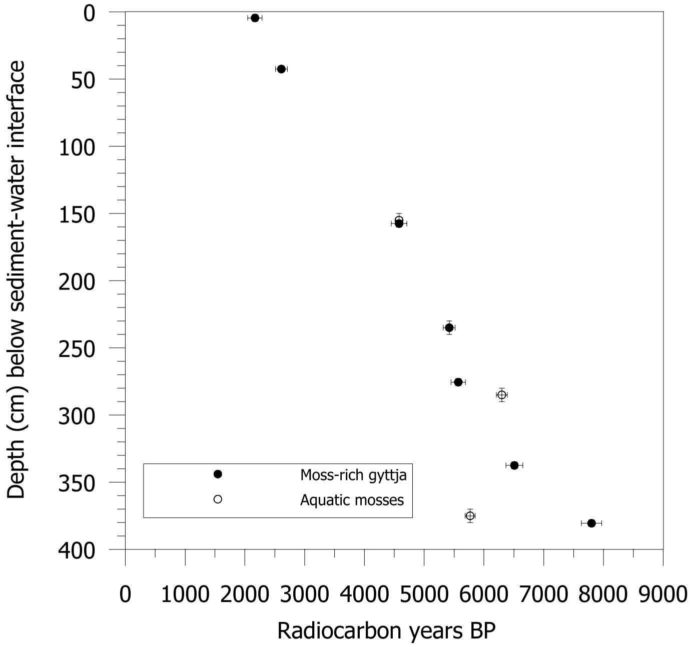

Figure 5. Radiocarbon measurements on bulk sediments abundant in aquatic mosses (open triangle) and on aquatic mosses (filled circle) from Lake Zano, Horseshoe Island, Antarctica (Björck et al., 1991b). One sigma standard error is shown for the radiocarbon age as well as depth errors. The moss-rich gyttja at the sediment surface yielded an age of 2170 ± 120 ^{14}C years BP. Note the varying age differences, which may be due to seasonal changes of reservoir effects (see text).

may be related to the presence of undetected, fine-grained coal particles. However, not all dates performed on mosses or moss-rich sediments seem reliable. For example, a ^{14}C dating series on bulk sediments rich in aquatic mosses, and pure mosses, from a lake on Horseshoe Island, at the south-western part of the Peninsula, shows an age of c. 2000 years for the surface sediments (Fig. 5) consisting of moss gyttja. With the exception of the lowermost dated level, it also shows that mosses and moss gyttjas attain similar ages. The implied reservoir effect of 2000 years is similar to the one found in the Dry Valleys lakes. The main inflow to this lake comes from a small glacier, which makes up one part of the lakeshore. During the corings, which were performed in the late part of the summer season, most of the lake was ice-free. The carbon reservoir of the lake water, especially the surface water, is thus probably fairly well mixed with the atmosphere in late summer. However, if the lake water mass is vertically separated by a thermocline, with cold glacial water (containing old CO_2) at the bottom, a reservoir effect would be expected for the mosses living on the lake bottom. It is also possible that, if the lake was largely ice-covered during the growing season of the dated mosses, uptake of CO_2 was mainly restricted to the CO_2 of the glacially contaminated lake water, thus causing the aging of the dated material. The anomalous lowermost level (Fig. 5) can be explained by well mixing of the water column with atmospheric CO_2 during the growing season for the mosses at 5700 BP (Fig. 5), while the lake was poorly mixed during the lifespan of most of the other remaining organic sediment-forming organisms.

Another type of lake reservoir effect found by the Antarctic studies is contamination of the lacustrine environment by a marine reservoir effect (e.g., Zale, 1994; Björck et al., 1991b). Because of the high marine reservoir effects of 1000–1700 years (see summary in Berkman et al., 1998) in Antarctic marine mammals and birds, coastal lakes may be severely "polluted" by heavily marine influenced particulate carbon from seals and birds colonising the lakeshore. For example, in Lake Boeckella in Hope Bay, attempts have been made to quantify the effect of penguin guano on the ^{14}C age of the sediments (Zale, 1994), and the apparent age was found to be at least 1600 years. The effect of this type of marine eutrophication and "radiocarbon pollution" is obviously related to lake size/lake volume, size of the animal colonies, the local marine reservoir effect, and the productivity of the lake itself. Although these Antarctic environmental scenarios are fairly extreme, it should not be ruled out that many landscapes during, for example, the glacial and deglacial periods might have been subject to similar conditions (Lowe et al., 1988). Consequently, radiocarbon dating of such records has to be carefully scrutinized.

Owing mainly to the presence of old CO_2 in the eruptive gases, the lake water and the surrounding vegetation in volcanic areas may be depleted in ^{14}C (Olsson, 1986). Radiocarbon ages on lake sediments and plants growing in the vicinity of volcanic emissions have been reported to be several thousand years older than expected (see e.g., references in Olsson, 1986 and Sveinbjörnsdóttir et al., 1992). Comparable AMS radiocarbon dates on terrestrial plant material and aquatic mosses from two lake basins on Iceland by Sveinbjörnsdóttir et al. (1992) varied by several thousand years, and modern mosses yielded radiocarbon ages of 6000–8000 years BP.

Hard-water reservoir effects

In areas with calcareous bedrock and/or soils, the lake water is alkaline and thus rich in bicarbonate ions. Aquatic plants will, during photosynthesis, take up and incorporate "fresh" carbon together with a smaller or larger fraction of this "dead", old carbon (Fig. 2). This so-called 'hard water effect' will result in considerably older radiocarbon dates (Figs. 6 and 7) compared to the actual time of deposition (Deevey et al., 1954; Shotton, 1972; Olsson, 1986; Andrée et al., 1986; Ammann & Lotter, 1989). This is thus another source of error, specific for hard-water lakes, in addition to the sources mentioned above. Several attempts have been made to quantify the hard-water effect along a sediment sequence. This can either be done by comparing radiocarbon dates on gyttja samples with those obtained on carbonates and plant macrofossils from within the same lake (Andrée et al., 1986; Ammann & Lotter, 1989), by parallel dating of bulk-sediment and terrestrial plant macrofossil samples on the same sediment core (Fig. 6) (see e.g., MacDonald et al. 1991b, 1991a; Barnekow et al. 1998; and Törnqvist et al. 1992), or by parallel radiocarbon measurements of the bulk sediment and the organic fraction (Geyh et al., 1998). These authors showed that the effect can vary considerably through time along a sediment sequence, and it seems thus almost impossible to estimate the 'true' age of carbonate-enriched bulk sediment samples. In some cases the hard water effect may not be obvious, because the effects are subtle and the sediments are more or less devoid of carbonates (Fig. 4). During such circumstances all possible clues have to be taken into consideration: pH of the water, proximity to a carbonate source, water depths, oxygen conditions and sediment type. Oxygen defficient bottom water in Lake

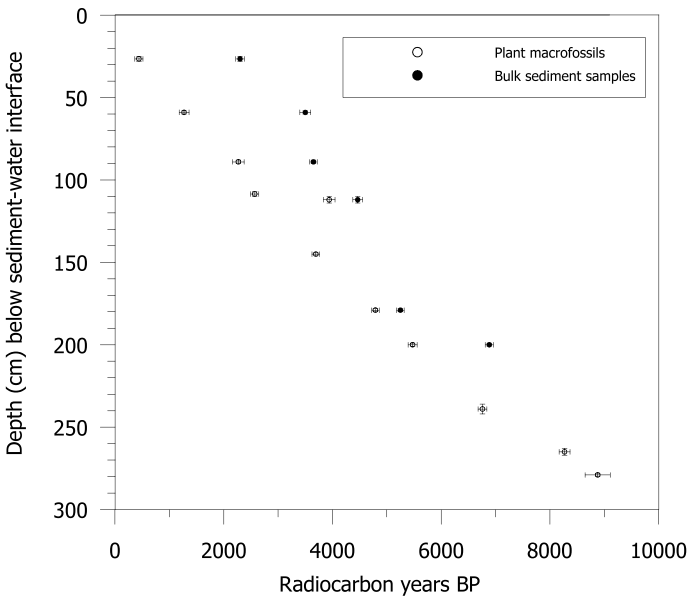

Figure 6. Comparison of AMS ^{14}C measurements on carbonate-rich bulk sediment samples and terrestrial plant macrofossils along the same sediment sequence in Lake Tibetanus, northern Sweden (Barnekow et al., 1998). The terrestrial plant macrofossil samples consisted of leaves of *Dryas octopetala*, leaves, catskin scales and twigs of *Betula* sp. and *Salix* sp. and of *Pinus sylvestris* needles. The lake possibly receives old dissolved inorganic carbon through groundwater and surface runoff from an outcrop of calcite marble situated close by. The smallest age difference between the two dating sets is at 1.78–1.80 m, where the sediment is enriched in terrestrial plant macrofossils. The carbonate content of the sediments is around 90% in the lower part of the sequence and decreases slightly upwards to between 40–80%.

Vuolep Njakajaure (Barnekow et al., 1998) may explain the absence of carbonates, and by partly using old DIC for assimilation, algae (which completely dominate the sediments) may account for a possible hard water effect (Fig. 4).

Given the scarcity of terrestrial plant macrofossils in some lake sediments, attempts have been made to use aquatic mosses, which were considered to prefer up-take of atmospheric CO_2 to obtain radiocarbon measurements on hard-water lake sediments. However, MacDonald et al. (1991b) could show (Fig. 7) that, in the case of extreme hard-water lakes, these specific moss samples yielded too old dates, but with a highly varying "error" in relation to the terrestrial dates. The reason for these old moss ages may, however, be complex (see Fig. 7 and figure text).

Sample storage, preparation and size

It is known that bacterial action is common on and in sediment cores stored at room temperatures or generally stored for a too long time. Bacteria may fix substantial quantities of CO_2 from the surrounding atmosphere, which then becomes incorporated in the sediment. Radiocarbon measurements, which are performed on such sediments, very likely result in younger dates than expected (Geyh et al., 1974). Contamination of foraminifera

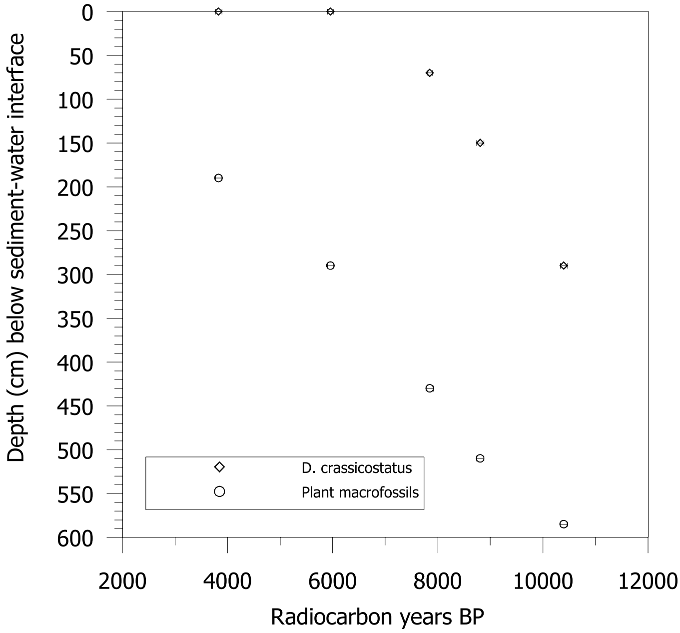

Figure 7. Comparative AMS ^{14}C measurements on aquatic bryophytes (*Drepanocladus crassicostatus*) and terrestrial plant macrofossils from the same sediment sequence in Lake Toboggan, western Canada (MacDonald et al., 1991b). While it has generally been assumed that these bryophytes do not take up ^{14}C-deficient carbon by incorporation of bicarbonates, the radiocarbon measurements on *D. crassicostatus* clearly show the unreliability of these mosses for radiocarbon dating. It is argued that the ^{14}C-deficiency of the mosses could originate from one or several of the following mechanisms: the generation of ^{14}C-deficient CO_2 through isotopic exchange, the formation of CO_2 from bicarbonate by chemical processes, and respiration and decomposition of aquatic organisms that have incorporated ^{14}C-deficient bicarbonate can generate isotopically similar CO_2 (MacDonald et al., 1991b).

and molluscs by modern carbon during storage has been reported by Olsson (1991), who suggested that such samples should be stored sealed off from the atmosphere. Wohlfarth et al. (1998b) showed that bacterial action and/or contamination by fungi might be a serious problem if terrestrial plant macrofossils are stored too long in water prior to the radiocarbon measurements. Bacteria/fungi are able to use their surrounding medium (water, air) for CO_2 uptake, which will then become incorporated in the radiocarbon sample. Dust particles, which may become mixed with the dated material during the preparation process, may be a further source of error. If a sample contains a fairly large amount of organic carbon and if the contamination is only minor, such an error is hardly detectable. However, samples with a low carbon content and a higher degree of contamination will result in considerably younger ages (Olsson, 1979; Wohlfarth et al., 1998b), as displayed in Figures 8a and b.

In order to avoid contamination of a sample by, for example dust, the preparation, extraction and determination of the macrofossils has to be performed very carefully. Wet storage of the selected macrofossils should be avoided in order to prevent bacterial/fungal activity and the sample should be dried at 100–110 °C as quick as possible (Fig. 1). This can

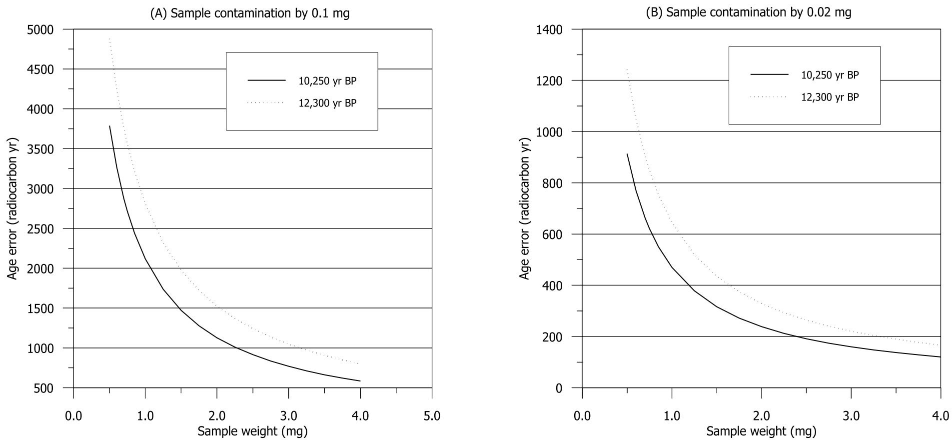

Figure 8. Resulting age errors of samples with expected radiocarbon ages of 10,250 and 12,300 ^{14}C years BP, respectively, and with a varying dry sample weight when contaminated by recent material in the order of (A) 0.1 mg, and (B) 0.02 mg (Wohlfarth et al., 1998b).

be done either in a clean glass bottle or on aluminium foil. To obtain a reliable measurement, the carbon content of the sample should ideally be $>$ 1 mg and $>$ 1 g for AMS and conventional datings, respectively.

Calibration of radiocarbon dates and procedures on reporting ages

After a few decades of experiences with radiocarbon dating and an increased number of radiocarbon measurements on tree rings from older tree ring chronologies (Pearson et al., 1986), it became obvious that the obtained ^{14}C ages did not correspond to the tree ring (or dendro) age, i.e. the assumed true calendar year age. We now know that these differences between calendar and ^{14}C ages are related to changes in the production rate of atmospheric ^{14}C, caused by the geomagnetic and solar influence on cosmic ray flux, and changes in global ocean ventilation rates (Stuiver & Brazunias, 1993). The added effects of these processes have led to significant age differences between calendar and ^{14}C years, especially in pre mid-Holocene time. Furthermore, these effects are occasionally also expressed as abruptly changing differences between the two time scales.

Apart from the obvious advantage of relating one's records to true ages, it is necessary to use a time scale with a constant length of a year when e.g., rates of change or true sedimentation rates are estimated. This often necessitates the use of calendar years, and therefore different attempts, procedures and programs for converting ^{14}C ages into calendar years have been developed over the years. These so-called calibrations have usually been deployed on ^{14}C dated and (assumed) calendar age based archives, such as annually laminated (varved) sediments and tree rings.

Today's internationally agreed radiocarbon age calibration record, INTCAL98, consists of radiocarbon dated German tree rings (oak and pine), covering the last 12,000 calendar years, in combination with ^{14}C dated laminated marine sediments and ^{14}C/U-Th dated corals (Stuiver et al., 1998) covering the time period between 12,000–24,000 calendar years. This record can be shown as a calibration curve (Fig. 9), displaying the relationship

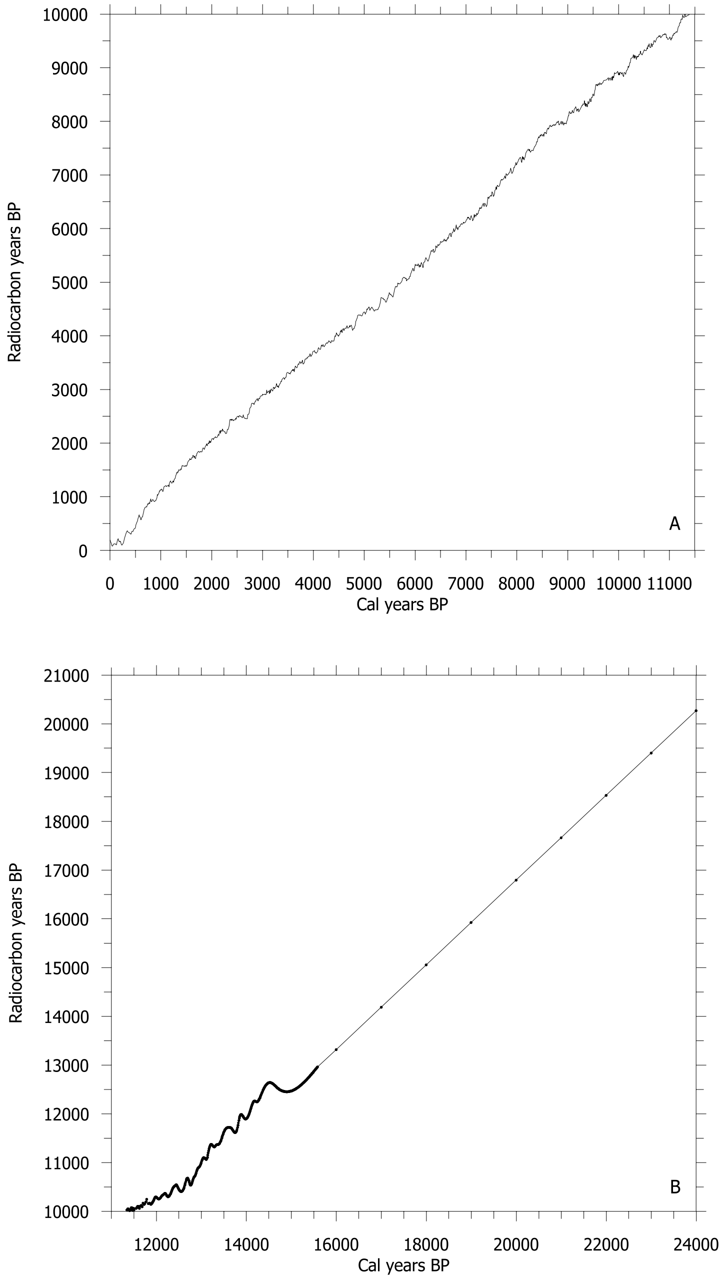

Figure 9. The INTCAL98 radiocarbon calibration curve (Stuiver et al., 1998), divided into (A) a Holocene and (B) a Late Glacial part. This calibration curve is based on a ^{14}C dated tree-ring chronology (back to 12,000 cal years BP), on a ^{14}C dated varved marine sequence (back to 14,700 cal years BP) and on paired ^{14}C/U-Th measurements on corals (back to 24,000 years BP).

between radiocarbon years and assumed calendar years through time, from which it is possible to obtain a fairly good estimate on the calendar age of a radiocarbon age. However, accurately calibrated ages for radiocarbon dates are obtained by analysing the dates with so-called calibration programs. These programs, which can be downloaded from the web sites of the ^{14}C laboratories in, for example, Oxford, Belfast or Seattle, are designed to give the statistically most likely calendar year time span for a specific radiocarbon age (with its reported confidence interval). The calibration results depend on the extent of the confidence interval of the reported radiocarbon age in combination with the confidence intervals of the radiocarbon and calendar dates of the time in question in the calibration data set, and the detailed structure of the calibration curve. The latter means that periods with rapidly changing ^{14}C ages will be more accurately dated (smaller confidence intervals) than periods with stable ^{14}C ages, so-called ^{14}C plateaux.

All calendar and radiocarbon ages are related to the year of 1950 (AD 1950). Regarding procedures in reporting calendar and ^{14}C ages, respectively, the former used to be related to BC (before Christ) and AD, while the latter was related to BP (before present=AD 1950). This meant that the calendar ages older than AD had to be added with 1950 years to be comparable with the radiocarbon dates and be related to the present, while the younger AD related ages had to be subtracted from 1950. However, now that many different types of more or less well-dated archives exist, it has lately become more common to clarify which type of years the time scale is based on and relate it to present time, i.e., AD 1950 (BP), such as ^{14}C years BP, varve years BP, ice years BP, calendar years BP, and calibrated (cal.) years BP.

Radiocarbon-dating different fractions of the sediment

The many uncertainties related to radiocarbon-dating bulk sediments and the difficulties that often arise when interpreting and comparing the obtained results have, in general, led to a more careful selection of the material that is submitted for radiocarbon measurements. With the introduction of the AMS ^{14}C technique, it has become possible to date carefully selected fractions of the sediment (Fig. 1).

In the following, we briefly discuss the advantages and disadvantages connected with different types of dateable material. The type of dating technique (decay/particle counting) chosen for the measurement will depend on the amount of material available for dating.

Macrofossils

Macrofossils found in limnic sediments derive either from the lake’s catchment, the lakeshore or from the lake itself, and may thus be part of both the autochthonous and the allochthonous fraction of the sediment (Fig. 2). Therefore, the macrofossils in lacustrine sediments are possibly more or less reworked and transported from the terrestrial and telmatic environment into the deeper parts of the lake, where the corings are usually performed. The underlying philosophy behind dating terrestrial macrofossils is, however, that the final reworking and transportation usually takes place fairly soon after the death of the organism in question. For radiocarbon dating, only macrofossil material from plants/animals, which use atmospheric CO_2 for their tissue up-building, should be selected (Törnqvist et al., 1992).

The sediment samples have to be sieved (under running water and through < 0.5 mm sieves) and the obtained organic material should preferably be identified to the species level (Fig. 1). This identification is important for a distinct separation between terrestrial, telmatic, and limnic plants. Furthermore, clearly reworked older material, such as highly corroded leaf fragments or wood pieces, may be present among the selected terrestrial macrofossils. It has been shown that especially wood fragments, which can with-stand erosion and thereby could have been part of several redepositional cycles before final deposition, may give considerably older measurements as compared to leaf fragments extracted from the same sediment level (Barnekow et al., 1998; Hajdas, 1993). If suspected old reworked macrofossils have to be submitted, it is advisable to perform a number of additional and reliable dates along the sediment sequence to assess any significant reworking effect on the ages.

In many cases sediments may be poor in organic macro remains. It can, therefore, be difficult to extract enough suitable plant fragments for dating. This has often led to thick columns of sediment being washed for macrofossils and resulted in radiocarbon dates representing perhaps 5–20 cm of sediment. For chronologic details, such dates are often unsatisfactory because of the lack of knowledge about the precise level from where the dated macrofossil(s) originate, but may be used for establishing rougher age estimates. One obvious way of circumventing the problem of detailed age control is to obtain a series of parallel cores at the same coring point. These cores are then precisely correlated with each other, primarily by lining up all the cores against each other, complemented by detailed sediment descriptions and routine sediment analyses such as measurements for organic carbon and magnetic susceptibility (see Sandgren & Snowball, this volume). If an accurate correlation can be achieved, the same stratigraphic levels may be sampled in all parallel cores with a very dense sampling strategy (0.5–2 cm). In this way, enough plant remains for dating may be extracted for a large set of thin sediment slices (see e.g., Andresen et al., 2000; Björck et al., 1996a), in spite of a restricted abundance of macrofossils.

Although much less common, it is also possible to use faunal remains for radiocarbon dating. For example, terrestrial insects extracted from lake sediments have shown to provide reliable radiocarbon dates (Elias & Toolin, 1990; Elias et al., 1991). A study, that focussed on the possibility to AMS radiocarbon date chironomid remains from soft-water lake sediments showed the potential and limit of this type of material (Jones et al., 1993).

In extremely organic-poor sediments, the search for dateable material may occasionally lead to surprising results. When it was found that a small part of the fine sand fraction in an Antarctic soft water lake on James Ross Island consisted of organic-like spherules of unknown origin (Björck et al., 1996b), they were not originally thought to make up the chronologic basis for the study. However, after several consultations with biologists/limnologists, it was discovered that these features were eggs of a freshwater crustacean, *Branchinecta gainii*, a today extirpated species on James Ross Island. Several hundred eggs were picked out from two sediment levels, which resulted in the possibly two most reliable ^{14}C dates from James Ross Island (Björck et al., 1996b).

Pollen

Pollen can be found in almost all limnic sediments and many local and regional pollen stratigraphies and stratigraphic correlations are based on pollen analytical investigations. It

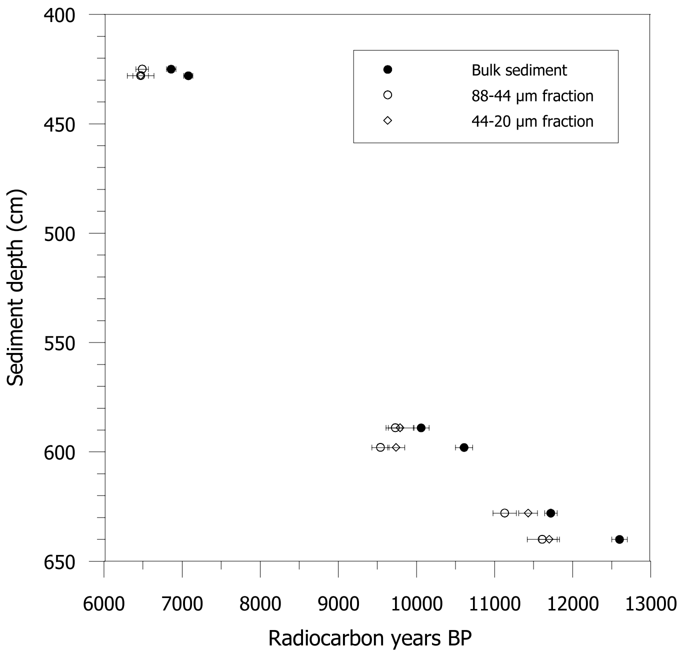

Figure 10. Comparative AMS radiocarbon measurements on bulk sediment samples and pollen concentrates by Brown et al. (1989). The dated fractions of the pollen concentrate (44–88 μm, 20–44 μm) mainly consisted of coniferous pollen grains. The preparation procedure is described in detail by Brown et al. (1989).

would, therefore, be of great value to directly date the pollen stratigraphic boundaries. Furthermore, the advantage of radiocarbon dating pollen as compared to macrofossils is that pollen are present in many different types of sediments and throughout a whole sediment sequence, while macrofossils may be sparse or irregularly present. Pollen are also predominantly of terrestrial origin and provide radiocarbon dates that are not influenced by lake reservoir effects. It was therefore not surprising that the successive development of the AMS technique and the possibility to radiocarbon date very small samples, resulted in exploring the possibility of obtaining AMS radiocarbon dates on pollen concentrates (Brown et al., 1989; Brown et al., 1992; Long et al., 1992; Regnell, 1992; Richardson & Hall, 1994; Mensing & Southon, 1999). In a pilot study by Brown et al. (1989), the samples were treated following normal pollen analytical preparation procedures, however, omitting the acetolysis step. Pollen concentrates were then obtained through step-wise sieving (88 μm, 44 μm and 20 μm) and bleaching of the residues. AMS dating was performed on the 88–44 μm and 44–20 μm fractions. The first results by Brown et al. (1989) were very promising and showed the potential of the method, as compared to bulk sediment radiocarbon dates (Fig. 10). Regnéll (1992) slightly modified the method by Brown et al. (1989) and made a comparative study, where the same sediment sample was divided into four sub-samples, which in turn were pre-treated in different ways. Because of the small pollen size in this study, AMS dating was performed on the fraction between 10–

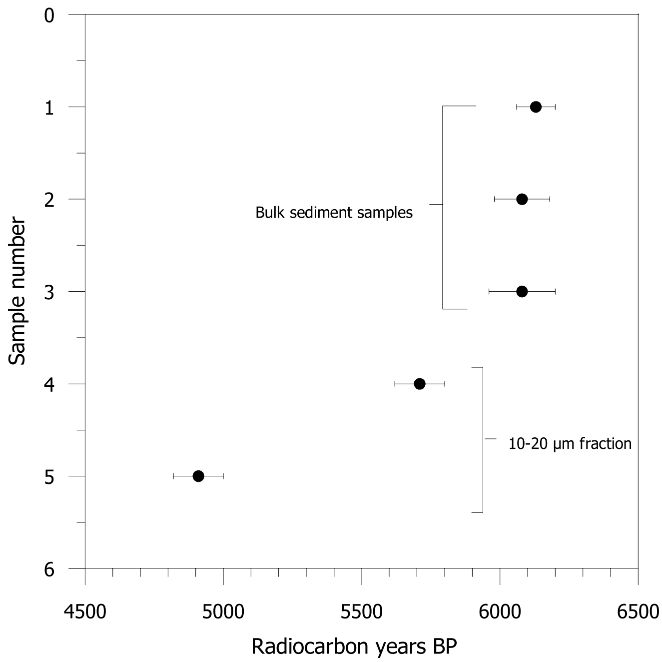

Figure 11. Radiocarbon dated pollen concentrates, based on the 20–10 μm fraction, by Regnéll (1992) with a slightly modified version of Brown et al. (1989).

20 μm. The results showed a clear age difference between bulk sediment and pollen concentrates, but also between pollen concentrates prepared in different ways (Fig. 11). Although these preparation procedures were able to remove as much non-pollen material as possible to obtain clean pollen concentrates, it was recognised that the concentrates still contained unwanted organic material. Regnéll (1992) therefore suggested that each sample should carefully be examined under the microscope before it is submitted for radiocarbon measurements. Several attempts have since then been made to remove non-pollen components in pollen concentrates. Long et al. (1992) suggested manual separation with a micromanipulator, Regnéll & Everitt (1996) presented a preparative centrifugation method, and Richardson & Hall (1994) a microbiological degradation method. Recently, Mensing & Southon (1999) presented a further development, which is based on a modified version of the pre-treatment procedure described in Brown et al. (1989). However, to clearly separate between pollen and organic detritus, which was still present in the concentrates after the different pre-treatment and sieving steps, they picked individual pollen grains under the microscope with the help of a mouth pipette. The picked pollen were stored in a vial, from which they were directly pipetted into quartz combustion tubes and dried in a vacuum centrifuge.

In general, these pollen concentrate studies yielded ages that were usually younger, in some cases significantly younger, than the corresponding bulk sediment ages, but in line with agreed upon ages from terrestrial macrofossils. Clearly, pollen concentrates have the potential to yield good dateable material. It is, however, crucial to know exactly what the samples consist of (i.e., to remove all non-pollen material before radiocarbon dating). In addition, it is a time-consuming method compared to many other ways of separately dating different parts of the sediment.

Alkali soluble (humic) and alkali insoluble (humin) fractions of a sediment

As a consequence of the many problems encountered in radiocarbon dating bulk sediments, Olsson (1979, 1986, 1991) developed a pre-treatment method, which allowed dividing the sediment sample into alkali-soluble (SOL) and alkali-insoluble (INS) fractions (Fig. 12). Her experience showed that the SOL fraction, which was likely to contain organic material from the time of the sediment deposition, yielded reliable ages for sediment samples, while the INS fraction, which contained old carbon material (e.g., graphite, coal) resulted in far too old ages. In contrast, for wood, charcoal, peat, and other macrofossils, the INS fraction proved to be more reliable than the SOL fraction.

Lowe et al. (1988) explored the possibility of AMS radiocarbon dating different fractions of sediment samples. They focussed on the humic acid fraction, lipid samples, residues of chlorite treatment (cellulose, mineral component), and residues of HF/HCl treatment (humin, mineral component). The resulting ages of the four investigated samples, which are displayed in Figure 13, show a clear tendency towards older ages than expected for the chlorite-treated and the HF/HCl residues. Since these two fractions contain mineral residues, they reflect the mineral carbon error inherent in the sediments. Walker & Harkness (1990) performed a comparative series of radiocarbon dates on the alkali soluble (humic) and alkali insoluble (humin) organic fractions on a sediment sequence from southern Wales. Their results showed, in general, older ages for the humin fraction (Fig. 14). Based on a detailed evaluation of their radiocarbon measurements, Walker & Harkness (1990) regarded the humin fraction, i.e. the alkali-insoluble fraction (INS), as giving more correct ages, which is actually contradicted by most other studies on this topic.

However, as shown by Björck et al.'s (1994) study, radiocarbon dating of different fractions does not always lead to clarifying results (Fig. 15), especially when dealing with sediments in areas with low aquatic productivity. The set of radiocarbon measurements from Lake Boksehandsken, eastern Greenland, which was performed on bulk sediments, plant remains, a marine mollusc, and the INS and SOL fractions, displayed dates for both fractions that were several thousand years older than the assumed deglaciation chronology, and with the INS fraction always being the oldest. It was also found that the age difference between the two fractions was positively correlated to the amount of carbon being burnt at higher temperatures. The organic carbon content of the samples was less than 2.5%, except for the three uppermost bulk samples, which had an organic carbon content of 4–> 8.5%. Björck et al. (1994) argued that the samples were contaminated by both old Quaternary reworked organic material, as indicated by an infinite age of plant material (see text in Fig. 15), and local Jurassic coal, of which the latter possibly makes up a significant part of the INS fraction carbon. The effect of these two carbon fractions thus becomes more severe the lower the carbon content of a sample is.

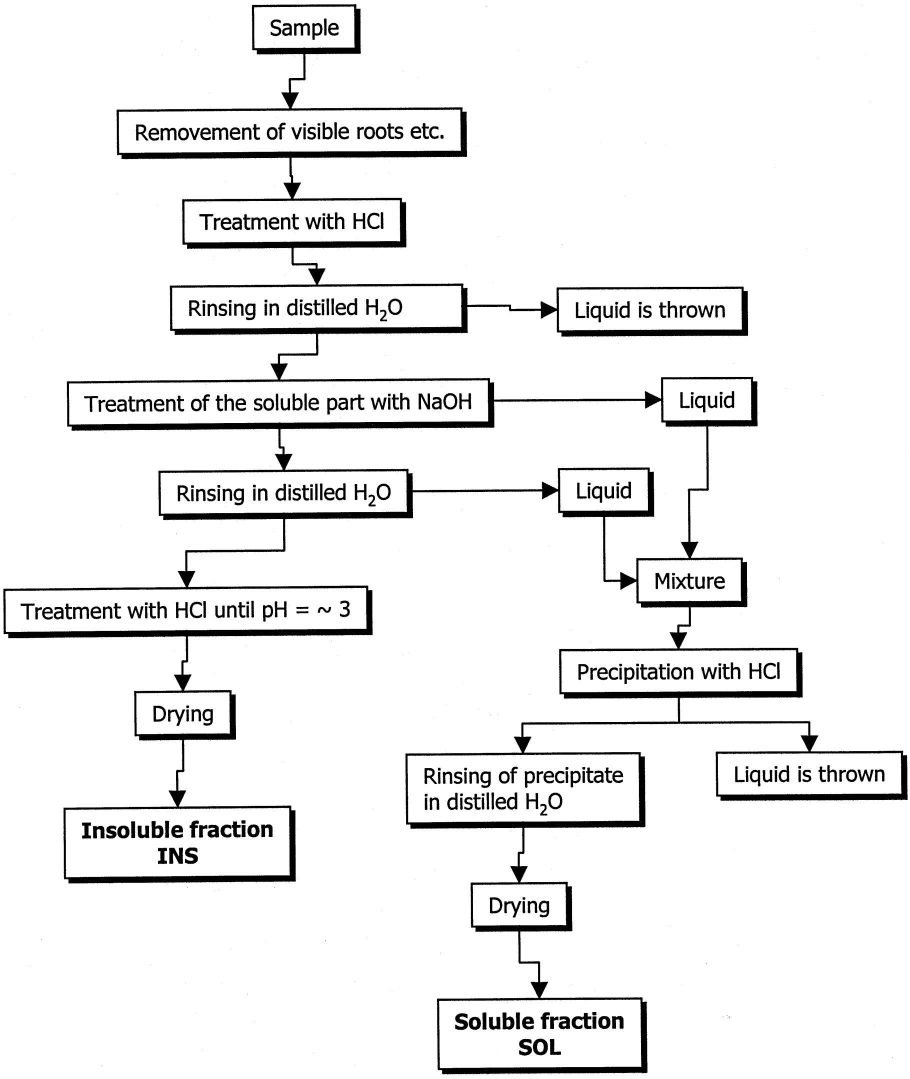

Figure 12. Pre-treatment scheme for bulk and plant macrofossils samples suggested by Olsson (1986, 1991). Although this pre-treatment has since then been slightly modified, the basic steps are performed in most radiocarbon laboratories. SOL = base soluble, humic acid, INS = base insoluble, residual, humin.

Hedges (1991) and Vogel et al. (1989) discuss the applicability of different sediment compounds for AMS radiocarbon dating and give further references. The study by Vogel et al. (1989) illustrated the large differences in ages obtained from different types of material and the complexity of radiocarbon dating different fractions of a sediment. However, except for dating the alkali soluble (humic) and insoluble (humin) fractions, little research has been performed on dating e.g., carefully extracted lipids.

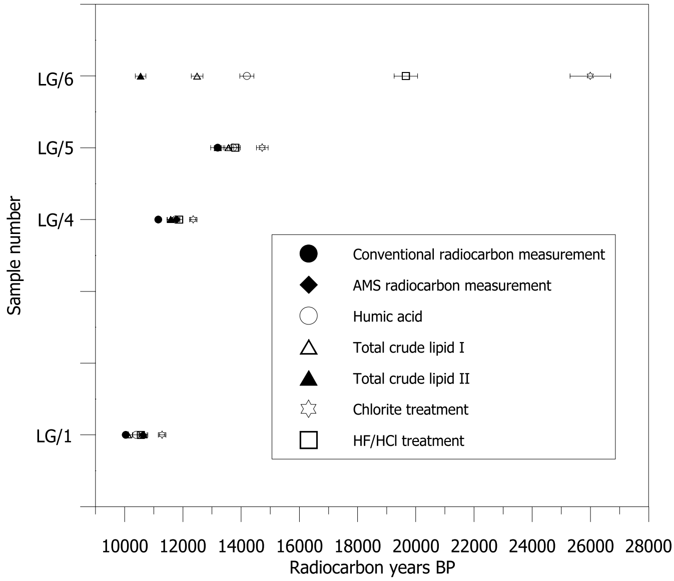

Figure 13. Measured AMS radiocarbon ages of various fractions of four samples from Llyn Gwernan (Lowe et al., 1988). The older than expected ages of the chlorite-treated (cellulose, residual mineral components) and the HF/HCl treated (humin/insoluble fractions, mineral components) samples are due to the mineral carbon error inherent in the sediments.

^{14}C as a chronostratigraphic tool

Long before the radiocarbon method came into general practice in the late 1950's, different ways of using lake sediments as geologic dating tools had already been in use. Changes in, for example, the lithology of the sediments were originally often used for correlations between areas and regions, since these were assumed to be synchronous. These lithostratigraphic correlations were often carried out on late- and postglacial sediments. Through more or less complicated and dubious correlations to the archaeological time scale, attempts were made to assess the age of the sediments. It was, however, not until the possibility of using pollen grains as a stratigraphic tool was formulated (von Post, 1916) and soon applied, that more secure correlations could tie lake sediments from different areas/regions to each other with the aid of certain distinct pollen assemblage changes. In the light of later knowledge, these pollen stratigraphic correlations, with their implied synchroneity, would, however, cause many problems for detailed chronological assessments and interpretations.

Although the sediment ages were uncertain, it should be noted that by combining an archaeological time scale with the clay-varve based Swedish Time Scale (De Geer, 1912), it was possible to build up a fairly well functioning chronology for the last 13,000 years (a period we now know spans ca 15,000 years (Wohlfarth et al., 1998a). The general apprehension of the length of the time period after the last glaciation was thus in the right order of magnitude, but the discovery of the ^{14}C method in 1951 (Libby, 1955) meant a revolution in Late Quaternary studies. This was perhaps especially true for scientists

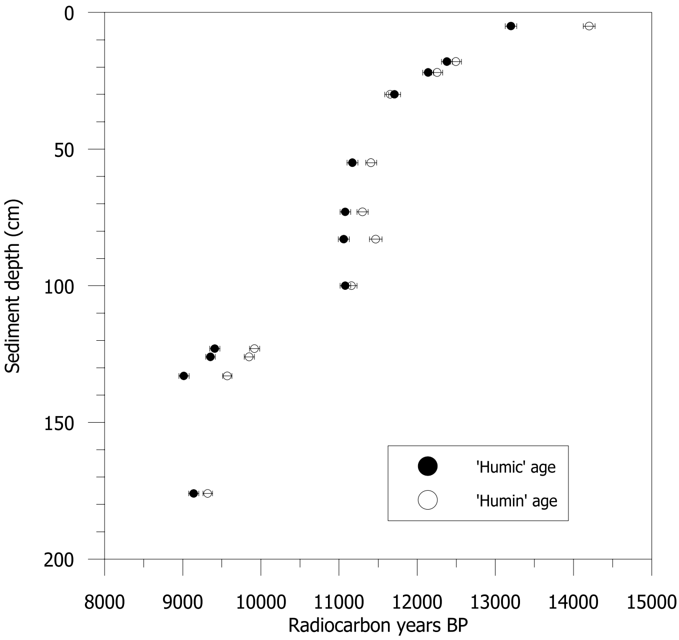

Figure 14. Comparative radiocarbon measurements on the alkali soluble, 'humic' (SOL) and the alkali insoluble, 'humin' (INS) fractions of sediment samples from Llanilid, South Wales according to Walker & Harkness (1990). Except for the lowermost sample, the radiocarbon measurements obtained on the insoluble (INS) fraction are in this study regarded to yield the most reliable dates. This conclusion is based on pollen stratigraphic considerations.

working with the often very organic rich lake sediments of the Late Quaternary. When Libby's (1955) original half-life of 5568 years was found to be erroneous (Godwin, 1962), the accurate half-life is 5730 ± 40 years, it almost resulted in a chaos of reported ages based on the two different half-lives. Since a large number of dates had already been calculated with Libby's half-life, it was fairly soon decided to report all ^{14}C ages, based on a half life of 5568 years (Mook, 1986).

As the number of new ^{14}C laboratories grew during the 1960's, an increasing number of radiocarbon dates became available from Holocene, but also late-glacial, lake sediments. One of the first obvious stratigraphic applications of the increased practice of radiocarbon dating organic-rich, pollen analysed lake sediments was that the previously defined pollen zones or pollen assemblage zones (p.a.z.) were gradually assigned secure ^{14}C ages. Since the Nordic countries had a strong Quaternary research tradition (and the region is abundant in lakes) it was hardly surprising that a ^{14}C-based Nordic chronostratigraphy was soon established for the last 13,000 ^{14}C years (Mangerud et al., 1974). It comprised a detailed chronostratigraphic sub-division of the Holocene time period and the Late Weichselian Substage and was based on a number of radiocarbon dates of significant pollen stratigraphic boundaries in lake sediments, but partly also in peat deposits, mainly from the Scandinavian countries. However, for the oldest dated boundary, the Bølling-Older Dryas chronozone boundary, the scheme was based on dates from Poland and Holland.

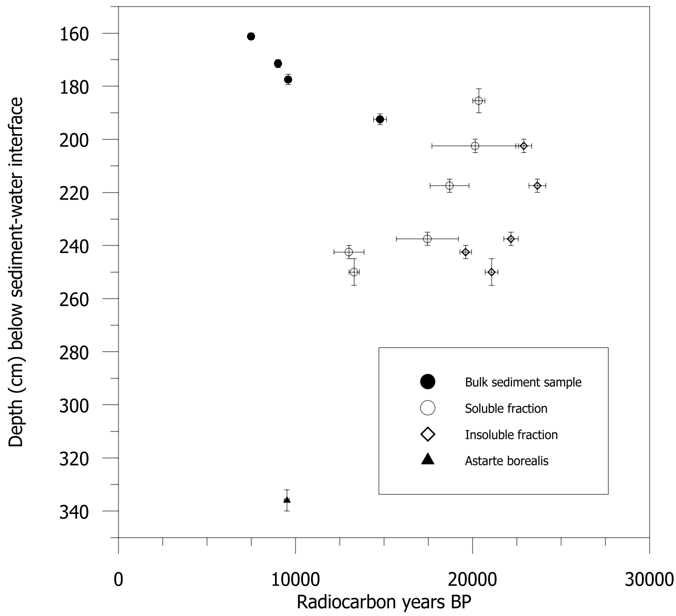

Figure 15. Comparative ^{14}C dates from Lake Boksehandsken, eastern Greenland (Björck et al., 1994). All datings were carried out by the conventional technique, with the exception of the lowermost dated level. Content of total organic carbon is 2–2.5% up to 181 cm, and gradually rises to 8.5% at 160 cm. From regional correlations, the sediments below 200 cm should not be older than 13,000 ^{14}C years BP, but rather be c. 10,000 ^{14}C years old, and are characterised by high sedimentation rates (Björck et al., 1994). Note that two further AMS datings were performed, one on plant remains at 180 cm gave an infinite age, and one dating on wood at 230 cm resulted in a ^{14}C age of 7130 ± 215 BP. While the former is regarded as reworked Quaternary plant material, the latter may be an effect of contamination from higher stratigraphic levels during coring.

The concept of the Nordic chronostratigraphic scheme grew strong and spread rapidly among Late Quaternary stratigraphers, and perhaps especially among Quaternary scientists working with late- and post-glacial lake sediments. In fact, the Nordic focus and basis for the chronostratigraphy was soon neglected or over-looked. Instead, it became a more or less world-wide applied system, being used for subdividing, for example, ice cores, marine sediments or loess deposits, and for correlations between these, and for example, northwest European lake sediments, with their often detailed climatostratigraphy and well-established ^{14}C chronology. The formal construction of this chronostratigraphic system was often challenged. Criticism usually focussed on the poor precision of the ^{14}C method in relation to the strictly defined chronozones (Björck, 1984) or its regional pollen- and climato-stratigraphically defined basis (Gray & Lowe, 1977; Broecker, 1992; Lowe, 1994; Wohlfarth, 1996; Björck et al., 1998b; Walker et al., 1999). It did, however, remain the dominating Late Quaternary chronostratigraphic scheme for more than 20 years. The main reason for this was probably its simply defined and user-friendly chronostratigraphic boundaries. It was obviously an easy system to work with, perhaps especially because many of the boundaries coincided with some main climatic/environmental changes, although this was one of the main points of concern from its critics. However, the gradually more detailed structure of the ^{14}C/dendrochronology curve showed the problems with well-defined ^{14}C dated boundaries; these may correspond to several 100 calendar year long periods of time because of decreasing $^{14}C/^{12}C$ ratios of atmospheric CO_2, which result in falling $\Delta^{14}C$ values. Although these features had been found in densely dated lake (bulk) sediment sequences, they were initially explained as an effect of reworked organic material or extremely rapid sedimentation rates (e.g., Oeschger et al., 1980); we now know that they represent so called ^{14}C plateaux.

With the onset of the 1980's, a new period in radiocarbon dating began (Muller, 1977; Hedges, 1978; Doucas et al., 1978), the era of AMS dating. It came as a result of the realisation that advanced nuclear physic instrumentation most significantly reduces the minimum amount of carbon demanded for obtaining radiocarbon dates.

By a dense series of radiocarbon dated terrestrial macrofossils in Swiss lake sediments (Ammann & Lotter, 1989), the existence of a long radiocarbon plateau in the later part of the Younger Dryas cooling was confirmed, preceded and followed by rapidly declining ages. As stated above, this had already been reported in 1980 from ^{14}C ages on peat (Oeschger et al., 1980), but Ammann & Lotter (1989) also noted a ^{14}C plateau from the Bølling Chronozone. These and other late-, and postglacial ^{14}C plateaux have later been found in several other lake sediment records (Björck et al., 1996a; Goslar et al., 1999; 1995a; Andresen et al., 2000). Periods with such radiocarbon features are obviously unsuitable for defining chronozone boundaries since many of the more distinct ^{14}C anomalies seem to correspond with time periods of climate change (Björck et al., 1996a; Wohlfarth, 1996). Because a large part of the Nordic chronostratigraphy is based on climatostratigraphic correlations, such a chronostratigraphic scheme is clearly outdated with today's high-resolution strategy. Furthermore, the discovery that fairly organic-rich bulk sediments, formed in soft-water lakes, which the chronostratigraphy largely was based upon, often yield too old ^{14}C ages compared to terrestrial macrofossil (see above), made the scheme even more questionable.

Most of the distinct Late Weichselian-Holocene climate events, which are recorded in the oxygen isotope record from the ice (and calendar) year dated Greenland ice cores (Johnsen et al., 1992; Alley et al., 1993), also seem to appear in marine and lacustrine sediment records. It is therefore now proposed to use the Greenland GRIP ice core as a stratotype for an ice year dated event stratigraphy (Björck et al., 1998b; Walker et al., 1999). Climatic events in, for example, lake sediments can thus, through normal geologic correlation principles, be correlated to the calendar (ice) year dated events in the ice cores.

Dating of long (old) stratigraphies

Due to the limits of the radiocarbon method and the availability of suitable sequences, the main focus has generally been placed on establishing good chronologies for the last deglaciation and the Holocene. The maximum age for radiocarbon dating (i.e., the lower limit of counting the activity of a sample) is laboratory dependent but corresponds to eight half-lives or approximately to c. 40,000–45,000 years, after which measurements become infinite (Geyh, 1983; Lowe & Walker, 1997). However, by applying a thermal diffusion isotopic enrichment, where the amount of ^{14}C in a sample is enhanced (Grootes, 1978), radiocarbon ages of up to 70,000 years BP could be obtained (e.g., Woillard & Mook, 1982).

This method requires fairly large samples, is time consuming and relatively expensive and has, therefore, not been widely applied.

Good radiocarbon measurements, with uncertainties of $< \pm 200$ years, have been obtained for the time period of the Last Glacial Maximum both with the AMS technique and the conventional decay method (e.g., Kitagawa & van der Plicht, 1998a, 1998b; Woillard & Mook, 1982). For some sequences a fairly low uncertainty has been possible to obtain even for records stretching further back in time (Ramrath et al., 1999; Kashiwaya et al., 1999). However, usually the uncertainty levels become much larger for ages $> 20,000$ years BP, which is due to the decreasing activity of the sample. A nice example, which shows the possibility of radiocarbon dating older sequences, is the study by Woillard & Mook (1982), who performed conventional radiocarbon dating on bulk sediment samples at the La Grande Pile sequence in France. The set of dates, which extends back to 69,500 (+3800/−2600) ^{14}C years BP, allowed assigning radiocarbon ages to the detailed pollen sequence covering the time period between the St. Germain II stage (Odderade) and the Last Glacial Maximum. The Grande Pile sequence was perhaps the first well-documented evidence for glacial variability, which would later be so well documented from the Greenland ice cores (Johnsen et al., 1992; Alley et al., 1993). While the uncertainty levels for the individual measurements range at around ± 300 years between c. 31,000–20,000 ^{14}C years BP, they amount to up to 1500 at c. 50,000 ^{14}C years BP (Woillard & Mook, 1982). A number of AMS ^{14}C measurements on samples from the long Lac du Bouchet sequence, covering the last glacial cycle, are also summarised in Creer (1991).

More recently, a series of AMS ^{14}C measurements have been obtained on the acid leached total organic fraction of sediment samples, which gave radiocarbon dates as far back as c. 41,000 years BP (Benson et al., 1997). In another study, selected terrestrial plant macrofossils reach ^{14}C ages of c. 33,000 years BP (Möller et al., 1999). However, the uncertainty levels of the measurements in both examples are fairly high and vary between 130–960 years and 170–2200 years, respectively. That the dating precision increases with the conventional decay counting technique is clearly shown by the ^{14}C dating series from the 18 m thick and 40,000 year long sediment core from Lake Tulane in Florida (Grimm et al., 1993). For example, five ages between 32,300–39,600 years BP have single sigma errors between 220–650 years. On the other hand, the amount of carbon needed for such precision demanded 10–20 cm thick sediment samples. This low resolution sampling causes a within sample precision of 200–600 years, which is largely inefficient for detailed chronologic assessments. However, by fitting a mathematical function to the 16 finite ages a reasonable age model was obtained (Grimm et al., 1993). Based on this model, a convincing case was made that distinct pollen changes in the Lake Tulane sediments could be correlated to the North Atlantic Heinrich events (e.g., Heinrich, 1988; Bond et al., 1992), and in this respect the Lake Tulane record is a pioneer study.

A large number of more or less contiguous AMS ^{14}C measurements, covering the time period between 525–41,890 ^{14}C years BP (Fig. 16), have been performed on plant macrofossils from the long sediment record obtained from Lake Suigetsu in Japan (Kitagawa & van der Plicht, 1998a; 1998b). The high quality of the datings and the relatively low uncertainty levels of the individual measurements (130–820 years for the time period between 20,630–41,890 ^{14}C years BP) show that it is possible to obtain high quality radiocarbon dates that far back in time (Kitagawa & van der Plicht, 1998a).

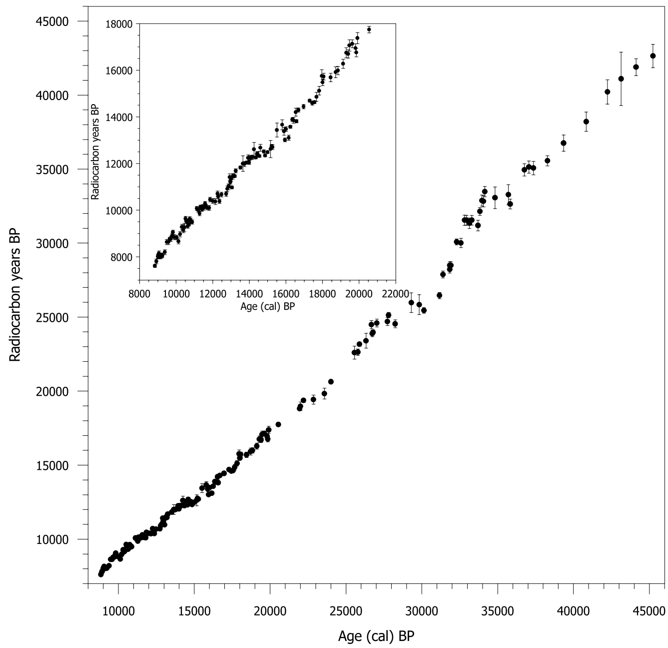

Figure 16. The ^{14}C dating series from the annually laminated sediment record of Lake Suigetsu (Kitagawa & van der Plicht, 1998b). Although the record also spans the whole Holocene, the curve only shows the time period between 7600–42,500 ^{14}C years BP (8800–45,000 varve years BP). The inserted curve shows the details between 7600–17,700 ^{14}C years BP. The laminations are caused by whitish diatom layers (spring growth) in otherwise dark clayey sediments. The annual chronology is mainly established through image analysis of digital pictures, and by different tests the counting error is estimated to $< 1.5\%$. The ^{14}C measurements (shown with 1-sigma bars) were performed on leaves, branches and insects of terrestrial origin.

High resolution dating and wiggle matching

The increased focus on high-resolution studies can partly be explained as a consequence of the new AMS dating technique, but is also a result of the now fairly good knowledge on the general chronologic framework of the late Quaternary. This has led to an increased focus on chronologic details. However, the discovery and increased apprehension of rapid (climate) change as an important player of the Earth system has probably been the most important factor in this respect.

In spite of very ambitious dating programs, the variable atmospheric ^{14}C content through time does pose problems in creating a detailed enough ^{14}C chronology. For the Holocene, this can partly be overcome by the so-called "wiggle matching method", where the varying ^{14}C content is used to tie the ^{14}C dates to the ^{14}C dated dendrochronology (for more theorethical details see Pearson, 1986). It usually involves a dense series of high-precision ^{14}C dates over fairly short time intervals, but is possible (but less secure) also over longer time periods, in attempting to replicate the shape of the ^{14}C/dendro curve. The method demands some extremely reliable ^{14}C dates (i.e., a dated material which was in contact

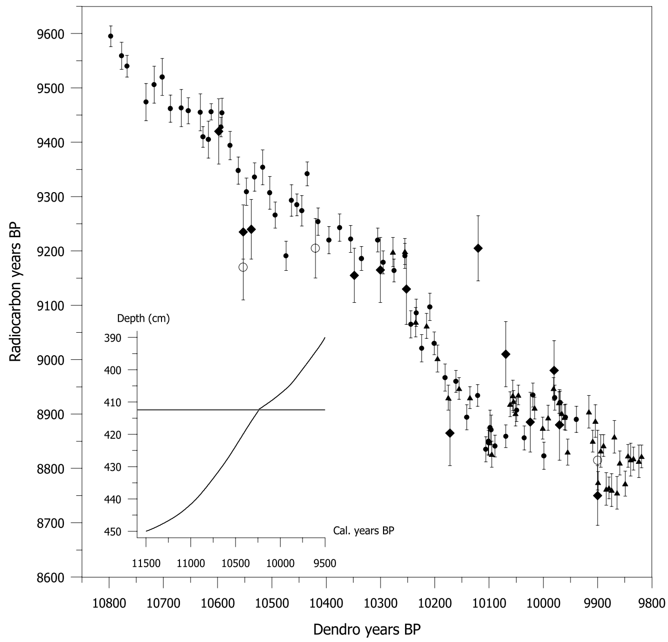

Figure 17. A high-resolution series of 13 ^{14}C dated bulk sediment samples (filled diamonds) and 3 samples of macrofossils (open circles) from Lake Starvatn on the Faroe Islands (Björck et al. in prep.), wiggle-matched to the ^{14}C/dendro curve (Stuiver et al., 1998), based on ^{14}C dates on German oaks (filled triangles) and pines (filled circles). The wiggle-matching is based on the inserted sedimentation curve. The sedimentation curve is based on the age of the Younger Dryas-Preboreal transition, a few calibrated ^{14}C ages (where a clear structure appears in the ^{14}C/dendro curve, see text) and the GRIP ice core age of the Saksunarvatn tephra (Grönvold et al., 1995). The tephra is seen as a horizontal line at 412 cm. All dates are shown with 1-sigma errors. One date falls outside the fit, which may be explained by e.g., reworked organic material, but could also be an effect of statistics.

with atmospheric CO_2 during its life-span and was buried in the sediments upon death) and/or one or a few dendrochronologically well-defined sediment horizons, such as well-dated tephra layers (Fig. 17). By, for example, anchoring the most securely ^{14}C dated levels to the calendar chronology via the dendro based calibration curve (Stuiver et al., 1998), it is possible to estimate sedimentation rates (calendar years/mm) for the interjacent sediments. The combination of ^{14}C age and calendar age is then plotted against the official ^{14}C/dendro curve to check the match between the curves. Since this may be closely related to sedimentation rates, the fit often involves minor adjustments of the sedimentation rates, before the most satisfactory solution is found.

To achieve the most secure dendrochronologic anchoring it is, if possible, adviceable to concentrate the ^{14}C dates to periods with large and rapid changes of the atmospheric ^{14}C content. This usually denotes shifts between periods of a radiocarbon plateaux (falling Δ^{14}C values) and rapidly younger ages (rising Δ^{14}C values). Since such shifts are often sudden and chronologically well-defined, both in ^{14}C and dendro years, they are thus the perfect anchoring points for the connection between dendrochronology and lake sediments. This means that an optimal wiggle-matching approach can and should be fairly well-planned with respect to ^{14}C dating; by checking the structure of the ^{14}C/dendro curve over the time period of study one can thus chose to date the part of the curve which shows most structure.

With respect to these types of very detailed comparisons between the "perfect" ^{14}C dates of the tree rings and one's own sediment based samples, it is important to present a brief sampling strategy and a simple quality evaluation of the dated material. Firstly, the sampling strategy for detailed ^{14}C work should always include saving a small piece of bulk sample from at least each sieved (for macrofossils) sediment level. This should be done since lake sediments are often barren in macro remains and bulk samples may prove to be reliable. If, for example, bulk sediments are the main basis for the wiggle-matching, which is often necessary to obtain dense enough dates (Gulliksen et al., 1998), they should originate from soft-water lakes. Furthermore, in such cases it is absolutely recommended that at least a few ^{14}C datings are performed on both bulk material and macrofossils from the same levels to test the reliability of the bulk material (Fig. 17). If the ages coincide, the potential for obtaining reliable and detailed chronologies for lake sediments is large. Thus, by combining a wiggle-matching approach with a dense sampling strategy for your lake proxy records, it is possible to achieve a very detailed calendar year based picture of whatever lake story one wants to mediate. It has been suggested that this method may date records within a few years certainty (Pilcher, 1991), but this is questionnable since it should be remembered that it is mathematically impossible to transform ^{14}C years into absolutely certain calendar years. This is due to the combined effect of the uncertainty (i.e. the confidence interval) of the ^{14}C age of several (5–10) tree-rings, and the smaller atmospheric ^{14}C variations.

^{14}C dating versus absolute dating techniques of lacustrine sediments

Annually laminated, varved sediments constitute an important palaeoenvironmental and palaeoclimatic archive, because they allow reconstructing environmental and climatic changes with high time resolution. Although the potential of this type of archive has long been recognised (e.g., De Geer, 1912; 1940; Renberg, 1976; 1981; Renberg & Segerström, 1981; Saarnisto, 1986 and references therein), an increased interest in studying laminated lake sediments can only be observed during the past c. 10–15 years (see references in e.g., Hajdas, 1993; Wohlfarth, 1996; Petterson, 1996; 1999; Kemp, 1996). This owes mainly to the fact that, in addition to being an annual archive for palaeoenvironmental and palaeoclimatic changes, many laminated lake sediments contain sufficient terrestrial plant macrofossils for detailed and more or less contiguous AMS ^{14}C measurements. These new possibilities led to exploring the potential of using AMS ^{14}C dated laminated archives to extend the dendrochronological calibration curve (Kromer & Becker, 1993; Becker, 1993; Stuiver & Reimer, 1993; Stuiver et al., 1998) back in time (Björck et al., 1987; Goslar et al., 1989; 1993; Hajdas et al., 1993; 1995; Kitagawa et al., 1995; Lotter, 1991; Lotter et al., 1992; Wohlfarth et al., 1993; 1995a). At present, well-dated laminated lake sequences are known from Japan (Kitagawa & van der Plicht, 1998a; 1998b), Switzerland (Hajdas et al., 1993; Hajdas, 1993), Germany (Hajdas et al., 1995), Sweden (Wohlfarth et al., 1993; 1995a; 1998a; Goslar et al., 1999), Poland (Goslar et al., 1999; 1995a; 1995b; 1993; 1989) and NW Russia (Wohlfarth et al., 1999). None of these laminated sequences is, however, continuous up to the present and several of them are interrupted by a hiatus or by non-laminated parts, and only a few of them can be regarded as suitable for radiocarbon calibration (e.g., Kitagawa & van der Plicht, 1998b; 1998a; Goslar et al., 1995b; 1995a). However, even these latter sequences are not continuous up to present and have to be tied to the Holocene part of the dendrochronological calibration curve by wiggle matching. Despite these shortcomings, several of the records can be used to reconstruct — for selected time periods — variations in the atmospheric $^{14}C/^{12}C$ content (Goslar et al., 1995a; 1999; Kitagawa & van der Plicht, 1998b). At present, the laminated sequence from Lake Suigetsu (Fig. 16) (Kitagawa et al., 1995; Kitagawa & van der Plicht, 1998b; 1998a) and the varved marine sequence from the Cariaco Basin (Hughen et al., 1998b; 1998a) are the most detailed ^{14}C dated sediment records, and of these Lake Suigetsu allows extending the dendrochronological calibration curve as far back as 40,000 years BP. Compared to the U/Th calibration curve (Stuiver et al., 1998), it gives a much more detailed picture on radiocarbon variations and radiocarbon plateaux, at least as far back as c. 35,000 ^{14}C years BP.

Radiocarbon dating of laminated lake sediments has also been performed on the most recent part of the Holocene. By a wiggle-matching approach, Oldfield et al. (1997) could simultaneously test the reliability of a lake varve chronology, and explore which of the components of the sediment gave the most reliable ^{14}C ages. A compilation of all available ^{14}C dated varve chronologies will soon be published in a forthcoming volume of *Radiocarbon*.

The increased use of U-Th dating (e.g., corals) from the last glacial cycle by thermal ionisation mass spectrometry (TIMS) has also led to explore its applicability for lacustrine sediments. Such studies have usually been concentrated on more or less pure lake marls, and have encountered problems with high levels of initial Th (Gascoyne & Harmon, 1992; Latham & Schwarcz, 1992; Lin et al., 1996), making age determinations highly uncertain. With a slightly different approach (Israelson et al., 1997), it was found that the algae-rich lake marls from Lake Igelsjön, in south central Sweden, seem to be suitable for U-Th dating (Fig. 18). The sediments contain 55–90% carbonates and 10–50% organic matter. This Holocene lake site is surrounded by Quaternary deposits, which are rich in locally occurring uranium-rich Cambrian alum shale and Ordovician limestone. The sediments show highly variable U-contents (6.8–75.9 ppm), and the peak values occur with the highest organic contents (70–80% of the uranium occurs together with the organic material). Furthermore, algae-rich marl seems to be an almost perfectly closed system; it is very elastic, dense and impermeable, preventing post-depositional movement of uranium. In addition, it is also fairly rich in macrofossils. Bulk samples were dated with U-Th, and macrofossils using atmospheric CO_2 were picked out for ^{14}C dating, followed by calibration. With the exception of a few samples with possibly reworked macrofossils (*Pinus* epidermis) and less dense sediment, the two different dating records coincide almost perfect (Fig. 18). Thus, if suitable sediments are at hand, this comparative ^{14}C/U-Th study shows that the U-Th method can be used in lake sediments as an excellent complementary dating tool to the ^{14}C method. It implies that carbonate-rich bulk sediments may be accurately dated (in calendar years) and the time-range of lake sediment dating could in this way be stretched far back in time, possibly as far back as 300,000 years. The potential of U-Th dating lake sediments older than 40,000 year was also shown in the study of saline lake deposits from Death Valley (Roberts et al., 1997).

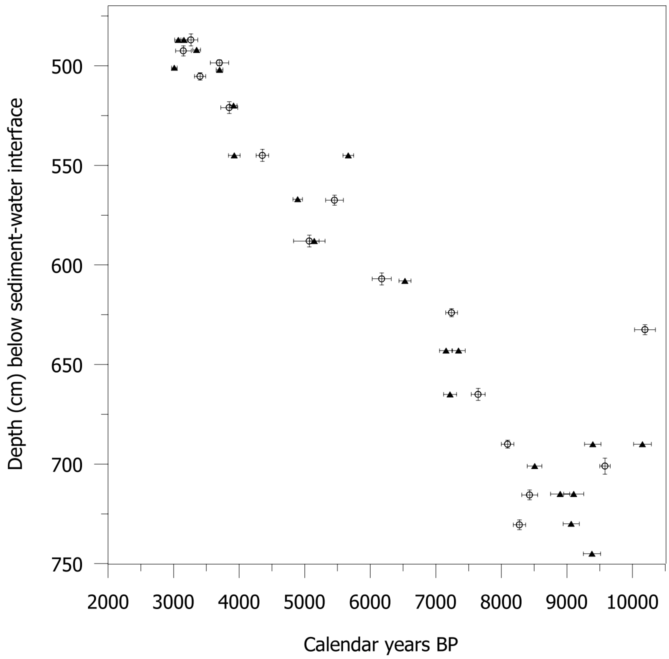

Figure 18. Two different dating sets from the algae-rich marl in Lake Igelsjön, south central Sweden (Israelson et al., 1997). The U-Th ages (filled triangles) were measured on 0.5 cm thin slices of bulk sediments, while the AMS ^{14}C ages (open circles) were measured on washed out terrestrial macrofossils, and calibrated to calendar years BP. In addition, the values for the U-Th ages were subtracted by 46 years; they were measured 1996 and calibrated ^{14}C ages are related to years before 1950. All ages are shown with 1-sigma errors. For more information, see text.

Concluding remarks

It is impossible to suggest a universal strategy for obtaining reliable radiocarbon dates, because each approach has to be adapted to the type of lake and sediment material that are to be investigated as well as to the objective of the study. However, before deciding the sampling and dating strategy, the following considerations should be made:

(1) Which type of organic material is available and in which quantity? If, as an example, the sample consists of > 1 g of terrestrial organic carbon, the conventional decay counting technique is probably preferable, because it generally gives more precise measurements and is slightly less expensive. In all other cases, the AMS ^{14}C method will be the better alternative (Fig. 1).

(2) How will the lake type and the sediment composition influence the radiocarbon measurement? Bulk sediment samples are, in general, subject to many uncertainties with respect to the radiocarbon dating result. Sediment samples from soft-water lakes may yield reliable measurements, but may also be exposed to different types of more or less subtle reservoir effects. More serious errors may result from incorporation of old or young carbon in the sediment. Bulk sediment samples from hard-water lakes will be prone to the same contamination effects as soft-water lakes. However, the most significant age error in these

types of lakes are due to the hard-water reservoir effect, which usually results in significantly too old ages. Because of these many uncertainties, the radiocarbon measurement should be performed on well-identified material in order to assess any sources of errors related to the dated material.

(3) What are the scientific objectives of the project in terms of dating? In most cases, radiocarbon measurements are applied to obtain a good chronology for the studied section or sediment core. In such a case, samples will have to be taken at certain levels along the entire section or core, but what is the desired time resolution? A detailed chronology demands a large set of dates, and, in our opinion, it is usually much more worthwhile to put the dating efforts into one well-dated sequence, which can also be used as a future reference site, than to split the efforts into several sites with low time resolution. Finally, a good chronology also means that the time period, which the sample represents, should be smaller than the quoted error obtained from the radiocarbon measurement, i.e., if a radiocarbon date is quoted with a standard error of ± 50 years, the sample submitted should ideally comprise < 100 years. With the AMS techniques now dominating, this should usually not be a big problem if the right sampling strategy is chosen.

Summary

The application of ^{14}C as a chronostratigraphic technique in paleolimnology is a vast topic and it is impossible to cover all possible aspects of this dating tool in relation to limnic sediments. In this overview, we have tried to focus on the most important and user-orientated aspects of the ^{14}C method. The extensive reference list on each of the addressed issues will, however, make it possible for the reader to explore the subject in more detail.

Lake sediments usually contain a certain amount of organic carbon in form of terrestrial, telmatic and limnic plant and animal debris and are, therefore, highly suitable for radiocarbon (^{14}C) dating. Since its discovery, ^{14}C dating has become the most widely applied chronostratigraphic tool in the study of late Quaternary lake sediment sequences. It allows obtaining an age control for the investigated sequences and enables comparisons and correlations on local, regional and global scales. Radiocarbon measurements are either performed with the conventional decay method, for which c. 1 g of pure carbon is required, or by the accelerator mass spectrometry (AMS) technique, where only a few mg of carbon are necessary. The background to radiocarbon dating, the advantages and disadvantages of both available methods, as well as a short historic overview and a "cook book figure" on the handling of a ^{14}C sample from the field to a dating result, introduce the main text.

Radiocarbon measurements are fairly expensive and often a series of dates will be performed along a sediment sequence. Therefore, each sample has to be carefully scrutinized (type of lake sediments, choice of sample material, sample treatment, size and storage, etc.), in order to obtain good results (Fig. 1). One section has, accordingly, been devoted to different types of errors, such as contamination by old and young organic material, general lake reservoir effects, hard-water reservoir effects, sample storage, preparation and size. Each of these possible errors, which can severely influence the age of a radiocarbon sample, are illustrated by examples from a variety of lake-sediment sequences from different geographic settings and time periods. Based on these examples different sources of error are discussed and special emphasis is placed on a comparison between bulk sediment dates and dates on terrestrial plant macrofossils. We round up this section with discussions on

and methods for calibrating radiocarbon dates. The reasons for the calibrations are the highly variable atmospheric $^{14}C/^{12}C$ content, which leads to large differences between radiocarbon and calendar years. It is therefore necessary to calibrate the radiocarbon dates with a calibration programme, in order to obtain calendar ages for a sequence.

In the following section we addressed and discussed the feasibility of radiocarbon dating different fractions of a sediment sample, which has been made increasingly possible through the development and application of the AMS ^{14}C technique. Terrestrial plant macrofossils, if available in sufficient amounts, are probably most suitable for radiocarbon dating. However, many sediment types may not contain sufficient amounts of plant macrofossils. Therefore, other types of material, such as faunal remains, pollen or other fractions of the sediments (e.g., the humin-insoluble, humic-soluble, lipid fractions), have been tested for radiocarbon measurements.

The final section, which addresses the application of ^{14}C as a chronostratigraphic tool, is introduced by an extended historic overview, including the development of the Holocene and Late Weichselian chronostratigraphic scheme, its applicability, potentials and limits. Based on a number of selected studies, where good quality radiocarbon dates could be obtained as far back as c. 40,000 years BP, the range limit and the accuracy of the radiocarbon method is discussed and illustrated for the time interval between 20,000–40,000 years BP. For the younger part of the ^{14}C time scale we also explore the possibilities for detailed radiocarbon dating. If a contiguous series of high-resolution and high-quality ^{14}C measurements is available, it can be tied to the dendro-based calibration curve through wiggle matching. This approach allows assigning calendar-year ages not only to each ^{14}C measurement, but also to the interjacent sediments and makes it possible to estimate the sedimentation rates in calendar years/mm for a sequence. A short account on ^{14}C dating of annually laminated lake sediments and on comparative ^{14}C and TIMS U-Th measurements on limnic sequences round up the final section. In the future the U-Th method may become the main complementary method to ^{14}C for dating older Quaternary lake sediments.

Useful www.addresses

The Radiocarbon Laboratory of the University of Waikato, New Zealand, has a nice home page with information about, among others, the radiocarbon technique, its application, age calculations and radiocarbon calibration. The FAQ section provides understandable information relating to radiocarbon dating for students and lay people who are not requiring detailed information about the radiocarbon dating method. The link section offers extensive links to radiocarbon laboratories on the WWW and to sample preparation labs, however, not completely updated.
http://c14.sci.waikato.ac.nz/webinfo/index.html

The home page of the journal *Radiocarbon* can be found at:
www.radiocarbon.org/

The two radiocarbon calibration programmes which are available can be downloaded from:
The Oxford Research Laboratory for Archaeology and the History of Art, calibration programme OxCal v3.4:
http://www.rlaha.ox.ac.uk/

University of Washington or University of Belfast, calibration programme CALIB 4.2: http://depts.washington.edu/qil/calib/

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