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Interpretation of lake sediment accumulation rates

KD Bennett[1,2,3] and CE Buck[4]

[1] *School of Geography, Archaeology & Palaeoecology, Queen's University Belfast, Northern Ireland, UK;* [2] *Queen's Marine Laboratory, Portaferry, Northern Ireland, UK;* [3] *School of Geography and Geosciences, University of St. Andrews, Scotland, UK;* [4] *School of Mathematics and Statistics, University of Sheffield, UK.*

Corresponding author:

KD Bennett, Department of Geography and Sustainable Development, School of Geography and Geosciences, University of St. Andrews, North Street, St. Andrews KY16 9AL, Scotland, UK.

Email: k.d.bennett@qub.ac.uk

Abstract: The pattern of ancient sediment accumulation in lake basins is usually determined for the sole purpose of obtaining a chronology of the sequence. We develop graphical representations of lake basins and how they fill with sediment in order to make generalisations about sediment patterns which can be used to distinguish those that relate to an aspect of changing environment from those that relate solely to the shape of the basin itself. Our goal is general observations that could lead to more robust interpretation of age-depth models from lake basin sediments. We show that in nearly all circumstances with constant sedimentation, the overall pattern seen at a central core should be one of decreasing rate of sediment accumulation, which tends to be constant towards the top. In most situations, the initial rate of sediment accumulation is particularly high, because of the basin shape. Observed rates of sediment accumulation that increase up the core should normally indicate increasing sediment input (either autochthonous or allochthonous). On the other hand, detailed information on basin shape is needed to break decreasing rates of sediment accumulation into components due to basin shape and decreasing sediment input. These considerations show that the pattern of sediment accumulation in a lake basin has intrinsic value as an indicator of environmental change and potential utility in chronology construction, but only when interpreted in the context of basin shape.

Key words: Lake sediment, age-depth model, accumulation rate, environmental change, Holocene, basin shape

Introduction

The availability of radiocarbon dating has enabled the development of chronologies from the sediments of thousands of lakes globally. Investigators typically obtain scientific age estimates (such as radiocarbon ages) from 5–10 samples per 10,000 years, and use these to build a chronology for the whole sequence in a process known as 'age–depth modelling' (Maher 1972; Bennett 1994; Blaauw and Heegaard 2012), thus obtaining age estimates for those features of the sediment that are of interest in a particular investigation. Building the chronology is a necessary step, because time and expense preclude the possibility of dating every sample of interest, scientific age estimates are uncertain and there are not always suitable samples available that relate to key transitions in the sequence; thus the ages of features between dated samples can only be obtained by statistical estimation. Each chronology must be constructed individually because sediment accumulation rates vary between lakes, and even within lakes, in a way that is apparently individual to the particular lake, or core, under investigation. As a consequence, reconstructing age-depth relationships relies on modelling accumulation rates, but the resulting chronologies are used only to provide age estimates for features between dated points, and to estimate accumulation rates for the sediment or entities such as pollen or diatoms trapped within it. Patterns of lake sediment accumulation themselves are typically not interpreted or seen as providing useful information about aspects of environmental change, and studies that have looked at variation in sediment accumulation rates have not considered the role of basin shape (e.g. Webb and Webb 1988; Goring *et al.* 2012).

In this paper, we aim to develop some theoretical considerations for how the sediment in a lake accumulates, to provide a background against which to test actual patterns of sediment accumulation. Such a background exists for bogs (Clymo 1984; Yu *et al.* 2003) but has hitherto been lacking for lake sediments. Understanding of lake sediment accumulation should drive development of more sophisticated age-depth models for use in chronology construction, as well as interpretation of changes in sediment for palaeoenvironmental reconstruction.

The pattern of sediment accumulation is a response to several external factors, encapsulated as one particular record. It may, therefore, not always be possible to break the observed record down into its contributory components, but it appears to be the case that some useful conclusions can be reached in many cases from simple initial assumptions. We also aim to demonstrate that, from such assumptions, the pattern of sediment accumulation in a lake can be interpreted in terms of environmental change, and thus holds more value and information than used solely in chronology construction. Separating the implications of basin shape from consequences of changing sediment input should also improve aspects of interpretation relevant for environmental change.

Previous work in this area began with Lehman (1975), who categorised lakes into several basin profiles, and then made assumptions about how they filled. One of his profiles ('frustrum') is equivalent to ours. Others assume that basin profiles remain unchanged as the basin fills. All his profiles, and our graphical representations, assume that the water surface area remains unchanged during filling. He demonstrated that some basin profiles produce large variations in sediment accumulation rate with constant sediment input to the lake, with maximum accumulation rate in the deepest part of the lake, reducing upwards. The influence of lake basin morphometry on this process, known as sediment focussing, has been further discussed by Carpenter (1983), Blais and Kalff (1995) and Johansson *et al.* (2007). Blais and Kalff (1995) showed that permanent sediment accumulation occurs in areas of low basin slope, which always includes the deepest areas (where slope is zero). The significance of basin morphometry for palaeoecological studies at particular lakes has been shown by Davis and Ford (1982) and Bennett (1983b).

We aim to provide a series of worked examples that will lay a foundation for the interpretation of age-depth models in terms of environmental change (particularly sediment supply). Information in age-depth models is currently used largely as the basis for chronology and not as records of environmental change themselves. It is envisaged that a wider understanding of the factors that lead to sedimentation following a particular pattern will also enable more informed consideration of where to collect cores, and the kind of additional information (such as basin shape) that is needed to interpret age-depth models more fully.

In what follows, all ages are given in calender years before present, defined as AD 1950, using the units ‘ka’ to indicate ages, and ‘kyr’ to indicate durations.

Theoretical background

Lake basins have a wide variety of form, depending largely on their manner of formation (Hutchinson 1957), but nevertheless they share certain important characteristics. First, we assume that lakes are filled with water, maintained at a certain level by outflow or balance of precipitation and evaporation. This water is displaced by sediment, so the level itself is not affected by the accumulation of sediment (although the volume of water is). Second, the cross-sectional area decreases continuously with depth, and is zero at the deepest point. Third, sediment, whether autochthonous or allochthonous, falls to the bottom, and is preserved there, accumulating upwards. It follows that (i) a given sediment supply over a given unit of time will be spread over an increasingly wide area as the basin fills; and (ii) that given constant sediment accumulation a central core should show a decreasing rate of sediment accumulation (deceleration) through time, as a consequence of the infilling (Blais and Kalff 1995). We develop simple graphical representations (discussed further below) to show how this happens, and how the shape of the basin interacts with the rate of sediment supply to determine the accumulation pattern seen at a central core.

Our treatment of sediment accumulation relies on the following simplifying assumptions: (i) that all of the sediment falls to the deepest part of the lake basin, and remains there, implying no accumulation on the sides of the basin above the altitude of the current level of sediment infill to the current deepest part (cf Lehman 1975); (ii) that the pattern of deposition is not affected by near-surface processes (such as wave action and aerobic decomposition). We discuss the consequence of relaxing these assumptions further below.

The mechanisms of compaction of lake sediments are poorly known, if at all. Some compaction of sediment might be brought about by settling of the sedimentary particles within a water matrix, displacing water, which would influence age-depth profiles to some degree. The effect of this is likely to be seen in a decrease in bulk density and an apparent increase of sediment accumulation at the top of the sequence, where the sediment is least compacted, and may even be loose. This influences only the very top of sediment profiles (of the order of centimetres), as measures of sediment water content and bulk density tend to be constant down profiles of many metres (e.g. Bennett 1983a; Giesecke 2005; Goring *et al.* 2012), indicating little or no further compaction after these few centimentres. It is difficult to see how sediment can become compacted further down the profile, as most of the matrix is water, which cannot be compressed to any significant extent at the pressures encountered in Holocene lakes. We therefore regard compaction within the accumulating sediment as negligible, except in the most recent sediments (Goring *et al.* 2012).

Finally, although lake basins do exist in which the cross-sectional area increases with basin depth, such sites are rare and we therefore exclude them from the analysis presented here. Two examples are Otjikoto and Guinas, in northern Namibia, which are solution lakes (Geological Survey of Namibia 2014). Sediments in Otjikoto have been investigated palaeoecologically (Scott *et al.* 1991).

One useful means of comparing basin shapes is by the ratio of mean depth to maximum depth, where mean depth is equal to volume/surface area (Hutchinson 1957), which is equivalent to finding the height of a cylinder that has the same surface area and volume as the lake in question. Measuring from the surface downwards, a cone has a mean depth ratio of 0.33, a hemisphere has a ratio of 0.67, and a cylinder has a ratio of 1.0. In the dataset of 46 lake basins from Washington State (NW USA) examined by Lehman (1975), 3 (6.5%) had mean depth ratios < 0.33 (so funnel-shaped), 39 (84.8%) had ratios of 0.33–0.67, and 4 (8.7%) had ratios > 0.67. Several datasets, summarized by Carpenter (1983), show similar ranges, but a dataset of 48 Swedish lakes summarised by Johansson *et al.* (2007) contains the unusually high proportion (69% of 48) of lakes more convex than a cone. There are clearly wide variations among lakes, possibly controlled by regional factors, such as bedrock and glacial erosion (as Hutchinson 1957 suggested).

The mean depth ratio, calculated as above, is not the same as the depth which has half the lake volume above and below, and cannot be calculated in any relevant way for lakes with cross-sectional areas that increase with depth (such as Otjikoto and Guinas). More generally applicable is the depth that has equal volume above and below (median volume ratio, termed 'mean depth' by Wetzel 2001). For a cone (with point down), as a proportion of the maximum depth from the surface down, this is 0.206 ($1 - \sqrt[3]{1/2}$), for a hemisphere it is 0.347 ($2\cos(4\pi/9)$), and for a cylinder it is 0.5.

We distinguish in this paper between the rate of accumulation of sediment volume within the whole basin (VSAR), which would be measured in units such as $\mathrm{m}^3\ \mathrm{yr}^{-1}$, and the rate of accumulation of sediment at the deepest point (DSAR), typically measured in units of $\mathrm{cm\ yr}^{-1}$. For a cylindrical basin, the two are equivalent, as a given sediment volume increase always gives the same sediment depth increase, but, for other basin shapes, these parameters are not equivalent.

Methods

Simple representations of lake sedimentation

In order to understand the pattern of sediment accumulation within lake basins, we have developed a series of simple graphical representations for stylised lake basins (of a range of forms) which are filled with sediment from the deepest point upwards. The lake forms chosen are circular in horizontal cross-section from the surface down to the deepest point, and have vertical profiles derived by rotating power functions of the form $y = x^n$, for $x > 0$, about the y-axis. We focus on functions from $x^{0.5}$ (which when rotated about the y-axis gives a funnel-shaped basin with mean depth ratio = 0.2; median volume ratio = 0.13) through $y = x$ (which gives a cone with V-shaped cross-section, mean depth ratio = 0.33; median volume ratio = 0.21) and x^2 and x^5 (with mean depth ratios = 0.5, 0.71; median volume ratios = 0.29, 0.39 respectively) to the vertical-sided profile of a cylinder (mean depth ratio = 1; median volume ratio = 0.5). For each form, since the basin surface area and depth are kept constant, the volume varies, from the funnel (least volume) to cylinder (maximum volume). The accumulating sediment surface is flat (horizontal).

We incorporated sedimentation in each stylised lake profile by calculating the depth of the sediment surface after intervals of time, initially using constant accumulation rate to fill 1/50 of the full basin volume in each of 50 time intervals. We then varied the proportion of fill between the 50 time intervals in order to illustrate the effect of a selection of sediment accumulation patterns that are likely to occur in the real world.

More formally, we consider three schemes for accumulation rates over time: constant, increasing and decreasing. In all cases we augment accumulation over $T = 50$ equal time units, $t_1, t_2, \ldots, t_{50}$, within which the entire volume, V, of the basin is filled. Thus, for constant accumulation rate the volume at time step i is

$$v(t_i) = v(t_{i-1}) + \frac{V}{T},$$

while for increasing and decreasing accumulation rate it is $v(t_i) = v(t_{i-1}) + t_i \times c$, and $v(t_i) = v(t_{i-1}) + (T - (t_i - 1)) \times c$, respectively, where c is chosen such that $\sum_{i=1}^{T} t_i \times c = V$.

The patterns in question can be divided into two broad groups by the nature of their accumulation rates: (i) those that vary continuously through time (decreasing or increasing), and (ii) those that vary discontinuously (step-like) through time (increasing then decreasing, decreasing then increasing, or increasing then constant then increasing).

Our graphical representations of stylised lake basins, filled under a range of sediment accumulation patterns, were implemented in R (R Core Team 2014) and are reported here in the form of graphical output, also generated in R.

Statistical age-depth modelling

To accompany the stylised lake basins, age-depth profiles are provided for a selection of real sediment sequences from published lake sediment cores. All age-depth modelling was carried out within the Bayesian statistical framework using Bacon version 2.2 (Blaauw and Christen 2011), with the IntCal13 radiocarbon calibration curve of Reimer *et al.* (2013).

Results

Our results are presented in two ways: (i) as lake profiles showing the height of the sediment surface after each of the 50 time intervals, and (ii) as a plot of sediment thickness against time. The range of behaviour is best appreciated by considering the difference between funnel-shaped (Figure 1A–D) and cylindrical basins (Figure 2A–D), then looking at the other shapes that fall between these extremes. The cylindrical shape is straightforward: the basin profile is invariant, so uniform VSAR (rate of accumulation of sediment volume within the whole basin) results in uniform changes in DSAR (rate of accumulation of sediment at the deepest point). In a cylindrical basin, if VSAR is increasing (or decreasing), DSAR increases (or decreases) in exactly the same manner. The funnel shape is more complex, because of the increasing surface area available for sedimentation on the basin floor as the basin fills, resulting in increasingly wider spread of the sediment (and thus thinner layers). When VSAR is constant, DSAR decreases over time, rapidly at first, but at a decreasing rate until DSAR is nearly constant (but actually always decreasing). If VSAR decreases, this effect is enhanced (a higher proportion of the total infill accumulates rapidly in the early stages, then DSAR falls). If VSAR is increasing (with our parameters), then the decrease of DSAR is reduced, but not reversed: DSAR is lower in each time period than in the preceding one.

[Figure 1 about here.]

[Figure 2 about here.]

The funnel-shaped basin, in particular, illustrates one of the main conclusions of this analysis. Given that the area for sedimentation becomes greater as the basin fills in, sediment deposited at time unit $t + 1$ is more thinly spread than that at time unit t, and so (when VSAR is constant) DSAR decreases. However the rate of reduction of DSAR tends towards a constant value, and maybe indistinguishable in practice from a linear pattern. Even increasing VSAR (within certain limits: see below) cannot overcome this pattern. We propose, therefore, that for most situations, and excluding the deepest parts of an original basin, we should expect a pattern of DSAR that is, in practice, indistinguishable from linear (Figures 1A–5A and corresponding curves in Figures 1D–5D).

Considering the other profiles, between the funnel and the cylinder, the cone (Figure 3D) shows a decrease in DSAR even when VSAR is increasing. Basins with cross-sections x^3 (Figure 4D), weakly, and x^5 (Figure 5D), more strongly, show an increasing DSAR as VSAR increases, tending towards the pattern seen for the cylinder (Figure 3D). In these graphical representations, the rate of increase in VSAR (with our parameters) is more than sufficient to overcome the effect of sediment being spread more thinly as the basin fills. The parameters we use (best visualised in the cylinder: [Figure 2A–D]) provide for a marked increase in VSAR. The x^3 cross-sectional basin (Figure 4A–D) has a mean depth ratio of 0.6, which is already higher than most real lakes (of the 46 examined by Lehman 1975, just 10 have a mean depth ratio >0.6). Therefore, even with high rates of increase in VSAR, only lakes that are unusually flat-bottomed (high mean depth ratio and median volume ratio) show a pattern of DSAR that increases over time. It follows that, for most situations, observed increasing DSAR should mean that VSAR is increasing over time, since this situation cannot arise solely as a consequence of the changing profile of the lake basin.

[Figure 3 about here.]

[Figure 4 about here.]

[Figure 5 about here.]

Step-like patterns of change in VSAR help refine these results (the two examples of funnel and cylinder are shown in Figures 6 and 7). Since we fill our basins with sediment that has a horizontal surface, all the basins become more flat-bottomed as they infill. Thus, in all cases, even with an original funnel-shaped profile, when VSAR increases after the basin is partially full, the upper part of the profile shows increasing DSAR (Figures 6B and 7B, corresponding curves in Figures 6–7D). All graphical representations show changes in DSAR when there is more than one point of inflection (two points when there is one change in VSAR [Figures 6A and 7A and

Figures 6B and 7B]; three points when there are two changes in VSAR, etc [Figures 6C and 7C]). It follows that, for basin shapes other than cylindical, the first point of inflection in the curve of changing DSAR is due to the combination of basin shape and VSAR, second and subsequent points are due to changing VSAR (and hence perhaps to changing sediment sources or materials). For a cylindrical basin, if such exists, all points of inflection are due to changing VSAR.

[Figure 6 about here.]

[Figure 7 about here.]

Discussion

In developing these graphical representations, we have made some simplifying assumptions that clearly influence our results and how they might be interpreted. There are no lakes with the perfect shapes that we consider, although some may come close: see López-Blanco *et al.* (2011). However, nearly all lakes have the common property that the horizontal cross-sectional area increases higher up the basin. As long as a given lake's vertical cross-sectional profile fits between the funnel and cylindrical shapes considered here, the way in which it fills with sediment will follow patterns within the envelopes shown for these profiles. The continuously decreasing DSAR (rate of accumulation of sediment at the deepest point) for uniform VSAR (rate of accumulation of sediment volume within the whole basin) is especially to be noted, as this will be the case regardless of the exact shape of the basin profile and regardless of whether the shape is regular or irregular, as long as the cross-sectional area increases upwards.

We infer from these results that all cases where DSAR increases with time (Figures 2, 4–5D; Figures 6–7D) must be the result of an increase in sediment input (whether autochthonous or allochthonous), and thus all such cases bear examination and discussion. It will often be the case that the timing of the increase can be related to other aspects of environments inferred from cores, and thus knowledge of DSAR can provide additional information about environmental change.

Decreasing DSAR values are more difficult to interpret. These are to be expected, to some degree, because of the increasing horizontal cross-sectional of lake basins as they infill. Whether the observed decrease in sediment accumulation can be accounted for completely by the basin shape, or is in part a result of changes in VSAR, cannot be determined without more information on either, and this is normally lacking. Water- and sediment-penetrating radar or high resolution seismic methods ought to be able to provide original basin profiles, in three dimensions, but to our knowledge there is no study where this has been done sufficiently completely to be able to compare theoretical basins such as ours with observed basin shapes and patterns of infill. Suffice to say that, currently, we normally lack the information to draw any conclusions about the controlling variables behind DSAR values that are continuously decreasing, tending to linear, with time.

DSAR profiles that have two or more points of inflection should indicate that some process has changed. In most situations, it is likely to be that VSAR has changed (and this must be the case for any portion of the record where DSAR is increasing). However, it may also be the case that a lake basin has a complex profile, better approximated as two (or more) different profiles nested within each other, such that the way sediment deposition is spread (more, or less, thinly) changes over time as the basin fills independently in each profile.

Another important assumption is that the basin in-fills with sediment from the deepest part, with a horizontal surface of accumulation. There is reason for thinking that this is the case in at least some situations (e.g. Gilbert 2003; Simonneau *et al.* 2014). In other lakes, sediment deposition may take place at all water depths, but with increasingly higher rates in deeper water, as shown by Lehman (1975). We have not allowed any deposition on the sides of the basin at water depths less than the current deepest part of the lake. As the basin fills in, the effect becomes reduced as the level of sediment approaches the surface (when deposition must be near horizontal). If sediment is accumulating on the sides of the basin, but decreasingly so as the basin fills, and VSAR is constant, this should result in the appearance at a central core of DSAR values that increase through time, because less sediment is deposited at the edges and more in the centre, relative to that which would have been expected just from the basin shape. Whether this increase is sufficient to exceed the decrease expected from the widening of the area of the sedimentation is something that can only be determined by a knowledge of the basin shape. We expect the effect to be least in steep-sided lakes (high mean depth ratio), because sediment does not accumulate on steep slopes (Blais and Kalff 1995) and in larger lakes (lower ratio of perimeter to total volume), and conversely greatest in small lakes with low gradient sides.

Water level changes may be a factor in some regions (e.g. Shuman *et al.* 2009; Shuman and Donnelly 2006), and this may affect the sedimentation process (Larsen and MacDonald 1993). If all, or most, sedimentation is confined to a horizontal surface, changing the height of the water column above this surface will not, by itself, affect the rate of sediment accumulation, although changing water levels might secondarily affect amounts of erosion and sediment input, or the deposition process.

We also assume that the pattern of deposition is not affected by near-surface processes (such as wave action and aerobic decomposition). This is likely only to be significant at the deepest point when a lake is almost completely infilled (or was only ever very shallow). Removal of sediment by decomposition is equivalent to reducing VSAR, and thus affecting DSAR in the same way as widening basin shape. Wave action would keep a certain proportion of the sediment in suspension, thus delaying the settling of sediment but not affecting the rate of accumulation unless the suspended load changes.

All of our graphical representations, but especially those with lower mean depth ratios, show clearly how rapid sedimentation is, with constant volume input rate, in the early stages of basin infill, because of the relatively small surface area of the deepest part of the lake basin. It is likely in many real lake basins that these small deep areas are filled in very quickly, so that the lake bed flattens out, leading to a larger surface area of accumulation. In other words, the mean depth ratio and median volume ratio of the remaining water body should tend to increase as the lake fills. One consequence of this is that finding a lake's thickest sediment by the common practice of coring 'in the middle' is unlikely to be successful. It may also be the case that such deep parts are infilled very rapidly by, for example, minerogeneric material from erosion during periods of deglaciation at higher latitudes, giving rise to apparent high sedimentation rates that may be consequences of basin shape rather than necessarily from large amounts of material or high VSAR. The diagrams of Lehman (1975) that show dramatic sediment focussing in basins of certain form and pattern of filling appear so dramatic because the amount of infill is plotted against depth. When the amount of infill is plotted against time (as in our graphical representations), the relative importance of the effect over the whole infill is much reduced. This is because the deepest part of the lake is a tiny portion of the total volume, so filling this in accounts for a high proportion of the thickness of the complete infill but a low proportion of the time needed for complete infilling.

Comparing graphical representations with real data

Kettlehole Pond is a small lake in southwestern Yukon, Canada, investigated by Cwynar (1988). At the time of survey, its water depth was 7.75m, and 4.45m of sediment was collected. The record was dated by 15 radiocarbon dates (McNeely and McCuaig 1991) of bulk sediment from homogenous brown gyttja. The age-depth model (Figure 8A) shows a pattern of DSAR that increases continuously towards the present. Even without knowing the basin morphometry, as long as the basin profile widens upwards, this must indicate steadily increasing VSAR throughout the Holocene. The rate of increase appears to be even more rapid than our graphical representation for a cylinder (Figure 2D), so must be more rapid than that shown in the more realistic basin shapes that increase in diameter upwards. Whether this is due to increasing autochthonous or allochthonous material cannot be determined from the data available, but appropriate investigations of the sediment should lead to a useful addition to understanding the changing Holocene environments at this site.

[Figure 8 about here.]

Tilo is a crater lake at 1545m above sea level in the Ethiopian Rift Valley, investigated by Telford and Lamb (1999). At the time of survey, it had a surface area of 64ha, maximum depth of 11m and current mean depth ratio of 0.64 (close to a hemisphere). Seven radiocarbon dates permit the reconstruction of an age-depth model (Figure 8B) that shows two phases of DSAR. The earlier phase, about 10ka to 6ka, has an accumulation rate of about 0.38 cm yr^{-1}, and the second, from about 6ka to the present, has an accumulation rate of about 0.12 cm yr^{-1}. Assuming that the lake basin profile widens evenly, this indicates that there was a change in the sedimentation processes at about 6ka, likely resulting from a reduced VSAR (cf. Figure 6A, D). The change appears to have been fairly rapid (within a few centuries and, both before and after, the crater infilled in a roughly linear manner, as would be expected for constant VSAR. Telford and Lamb (1999) note a change in water quality after about 6ka, indicated by the diatoms, towards a more saline lake system, and their stratigraphy shows a shift in the sediments by reduced carbonate content and higher organic and mineral matter content. Telford and Lamb (1999) also noted the rapid change in accumulation rates of the core materials, which they relate to changing water levels. We suggest that the age-depth model itself is sufficient to make this point, which then makes it possible to treat the two phases of sedimentation separately, with possibly differing compositional relationships, such that calculated accumulation rates of individual proxies either side of the change may not be comparable because different sediment sources are involved.

Vestre Øykjamyrtjørn is a small lake in southern Norway at 570m above sea level (Bjune 2005; Velle *et al.* 2005). At the time of survey, it had a current maximum depth of 8m and surface area of 1.8ha (mean diameter ca 150m). The core of 3.6m was dated with nine radiocarbon dates (Bjune 2005). The age-depth model (Figure 8C) shows an overall sigmoidal pattern, with DSAR first steadily decreasing, then steadily increasing towards the top, with the point of inflection at 200 cm depth. The overall pattern resembles our representations of decreasing then increasing sedimentation in a basin with a profile more flat-bottomed than a cone (e.g. Figure 7B, D). The sediment stratigraphy (Velle *et al.* 2005) indicates that the lowermost sediments are more minerogenic, but the proportion of organic matter increases upwards until about 7.5ka, and then remains high towards the top. However, the steadily decreasing DSAR during this period might be a consequence of the basin shape, and cannot be further interpreted without more information on that, although the sediment record suggests that the decreasing DSAR might be due to reduced minerogenic input to the lake. The later Holocene part of the record, with steadily increasing DSAR must be the result of increasing VSAR, and minimal change in the sediment composition during this period indicates that the main cause of the change is likely to be increasing lake productivity (autochthonous sediment).

Vikjordvatnet is a small, deep lake in northern Norway, investigated by Balascio and Bradley (2012). At the time of survey, its water depth was 21m, the lake was 300m in diameter, and had 3.01m of sediment. It was dated with nine radiocarbon dates in the upper 2.32m of sediment. Age-depth modelling (Figure 8D) shows a pattern of DSAR that is very nearly linear, arguably with slightly lower values in the earliest and most recent part of the sequence, giving an overall weak sigmoid pattern of DSAR. Bearing in mind that only a small part of the basin has been infilled, and the radiocarbon-dated portion does not include the very earliest material collected, such a linear record of DSAR should mean either that the lake is cylindrical and flat-bottomed and VSAR has been uniform (Figure 2A, D), as more funnel-shaped lakes would show a curved age-depth relationship in the lower part of the basin infill, or that the lake is more funnel-shaped and VSAR is increasing (Figure 1B, D). More data on the lake basin shape is needed to separate these possibilities. The weak sigmoid aspect of the shape, if verified (more radiocarbon dates would be desirable), suggests that VSAR might have increased slightly early in the Holocene, and decreased late in the Holocene.

Conclusions

Simple graphical representations of the sedimentation of stylised lake basin forms lead to idealised plots of sediment thickness against time with which real age-depth models can usefully be compared. Our two key observations are that, for the over-whelming majority of basin profiles, DSAR (rate of accumulation of sediment at the deepest point) should decrease upwards, with a trend that tends to linear towards the top, and that, if any other pattern is seen, changes in VSAR (rate of accumulation of sediment volume within the whole basin) should be suspected. Consequently, since age-depth models are DSAR functions, they may well contain information beyond their usefulness as chronologies, and thus be informative about processes and rates of whole-lake sedimentation. Investigators should be confident with drawing immediate conclusions about VSAR where DSAR increases towards the present. Other conclusions on changes in VSAR may require knowledge of the original basin shape, and perhaps its changing shape as it infilled. If it can be assumed that the shape is simple, then age-depth models with two or more points of inflection are also revealing about whole-lake sedimentation. Our results are relevant also for the construction of age-depth models. In principle, it should be possible to generate an age-depth model from knowledge of the basin profile, a single basal age determination, and an assumption of constant sediment input. Any deviation from such a model would be indicative of changing sediment input.

Interpretation of DSAR values that decrease towards the surface are more difficult, as this will occur both as a basin infills (but at a rate depending on basin shape) and as a result of decreasing whole-lake sedimentary input. Observed age-depth models (DSAR) are constrained by both basin shape and VSAR, so interpretation of changes in DSAR can only be made in terms of one of these if certain assumptions can be made about the other. Further progress in determining changes in VSAR cannot be made without understanding of the original basin shape and how this changed as the lake infilled. Although determination of some basin shapes has been made possible by echo-sounding (Gilbert 2003; Moernaut *et al.* 2010; Simonneau *et al.* 2014) and seismic (Fuchs *et al.* 2004) methods, these techniques have not developed to the point of routine use, and certainly few palaeoecologists attempt this, although it would greatly assist in ensuring that the deepest sediments were cored. Technical problems exist with the recognition of water–sediment and sediment–bedrock interfaces, and there are complications with layers of gas bubbles, tephras, and other included atypical materials. Nevertheless, understanding basin shapes is essential in order to make further progress with the analysis and interpretation of reconstructed age-depth relationships in lake sediments.

The considerations in this paper show clearly that much work is needed in order to understand, and make reasonable inferences from, the accumulation of sediment in lakes. Substantial advances would be made by whole basin studies of basin morphology and sediments, including sediment composition and chronology of sedimentation. Much of this should now be feasible with various techniques for survey from the lake surface, but would have to be supplemented by coring and dating. The focus should be on the kind of small lakes, filled with organic gyttja (mostly autochthonous), that form the bulk of palaeoecological investigations, rather than the large lakes with inorganic sediment (mostly allochthonous) that have, so far, been the sites of most geophysical investigations. Such investigations would generate the data to test the considerations in this paper, and make possible more sophisticated and/or robust representations of how sedimentation actually occurs. Only then will it be possible to separate lake basin morphology from changes in sediment production or input as factors lying behind changes in rates of accumulation in central cores.

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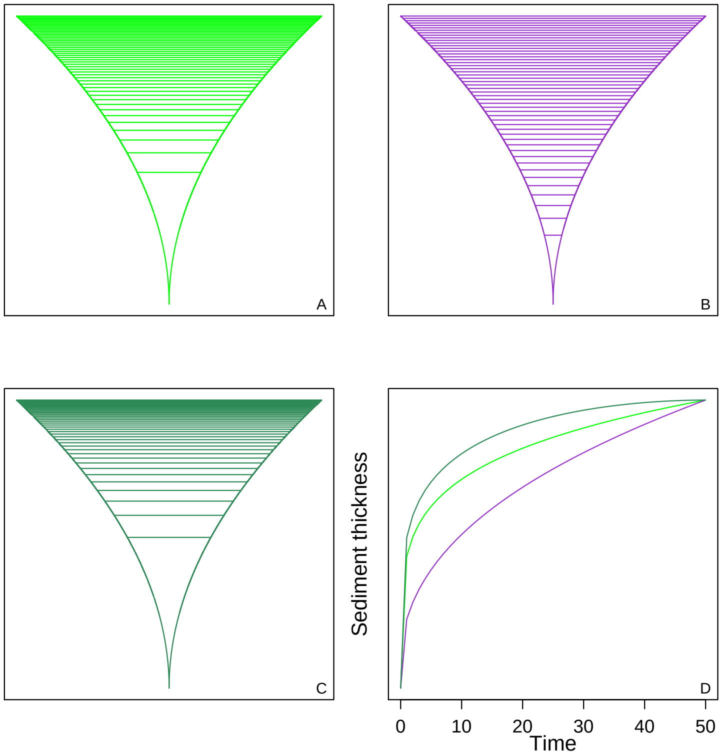

Figure 1 Graphical representation of sediment accumulation in a lake basin of circular surface area and funnel-shaped profile (obtained by rotating $y = x^{0.5}$ for $x > 0$ about the y-axis) over 50 units of time. A: profile of lake with constant sediment input per unit of time. B: profile of lake with sediment input (VSAR) increasing constantly through time. C: profile of lake with sediment input (VSAR) decreasing constantly through time. D: pattern of sediment accumulation at the lake centre through time (DSAR) (curves coloured to correspond to profiles in A, B and C).

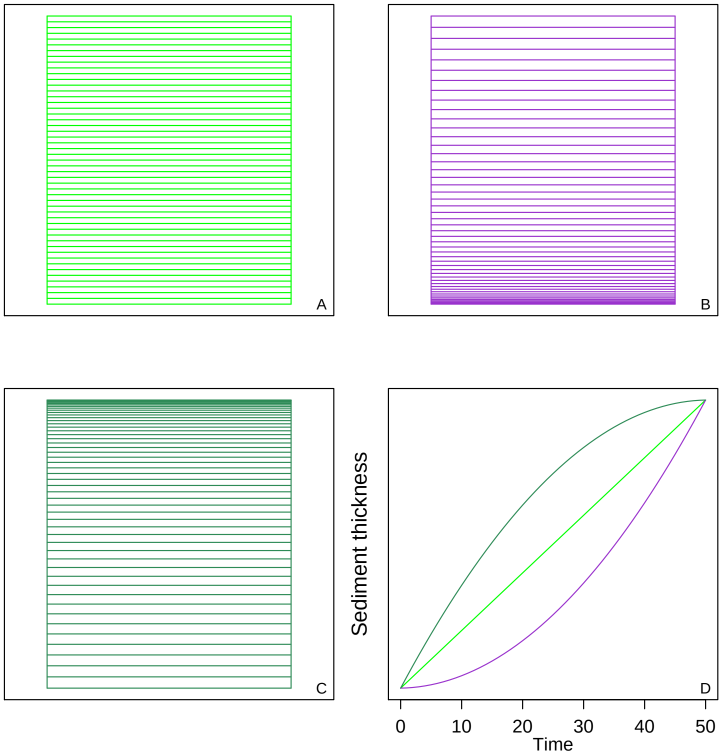

Figure 2 Graphical representation of sediment accumulation in a lake basin of circular surface area and cylindrical profile over 50 units of time. A: profile of lake with constant sediment input per unit of time. B: profile of lake with sediment input (VSAR) increasing constantly through time. C: profile of lake with sediment input (VSAR) decreasing constantly through time. D: pattern of sediment accumulation at the lake centre through time (DSAR) (curves coloured to correspond to profiles in A, B and C).

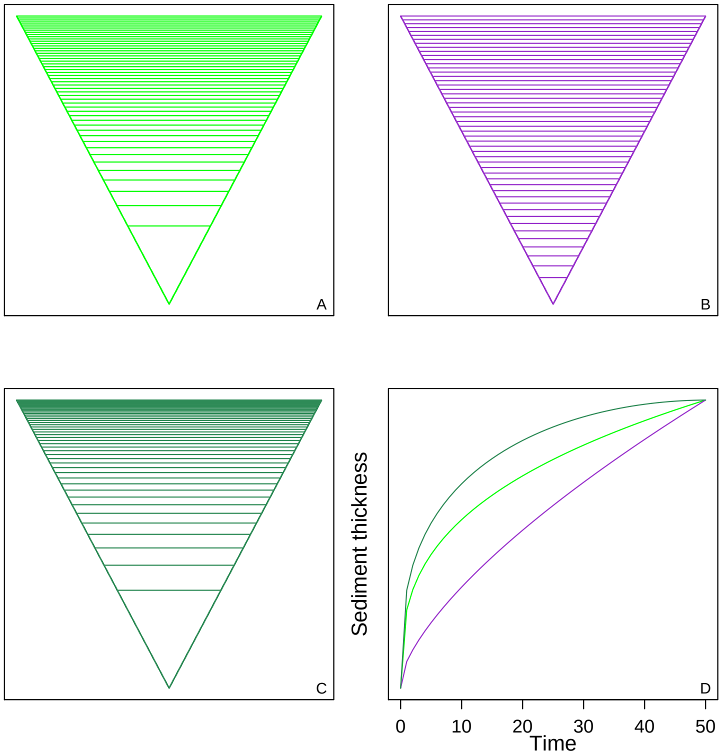

Figure 3 Graphical representation of sediment accumulation in a lake basin of circular surface area and conical profile (obtained by rotating $y = x$ for $x > 0$ about the y-axis) over 50 units of time. A: profile of lake with constant sediment input per unit of time. B: profile of lake with sediment input (VSAR) increasing constantly through time. C: profile of lake with sediment input (VSAR) decreasing constantly through time. D: pattern of sediment accumulation at the lake centre through time (DSAR) (curves coloured to correspond to profiles in A, B and C).

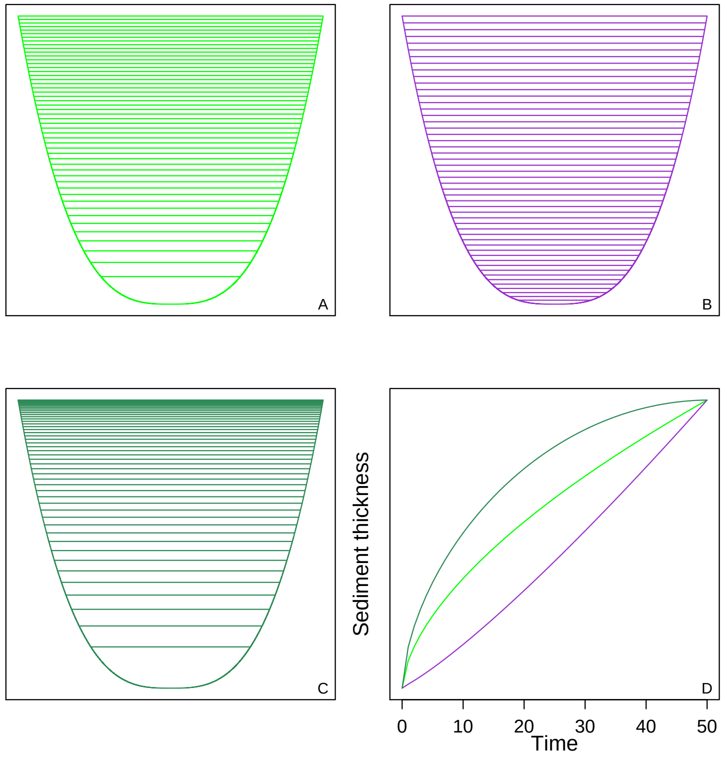

Figure 4 Graphical representation of sediment accumulation in a lake basin of circular surface area and concave profile (obtained by rotating $y = x^3$ for $x > 0$ about the y-axis) over 50 units of time. A: profile of lake with constant sediment input per unit of time. B: profile of lake with sediment input (VSAR) increasing constantly through time. C: profile of lake with sediment input (VSAR) decreasing constantly through time. D: pattern of sediment accumulation at the lake centre through time (DSAR) (curves coloured to correspond to profiles in A, B and C).

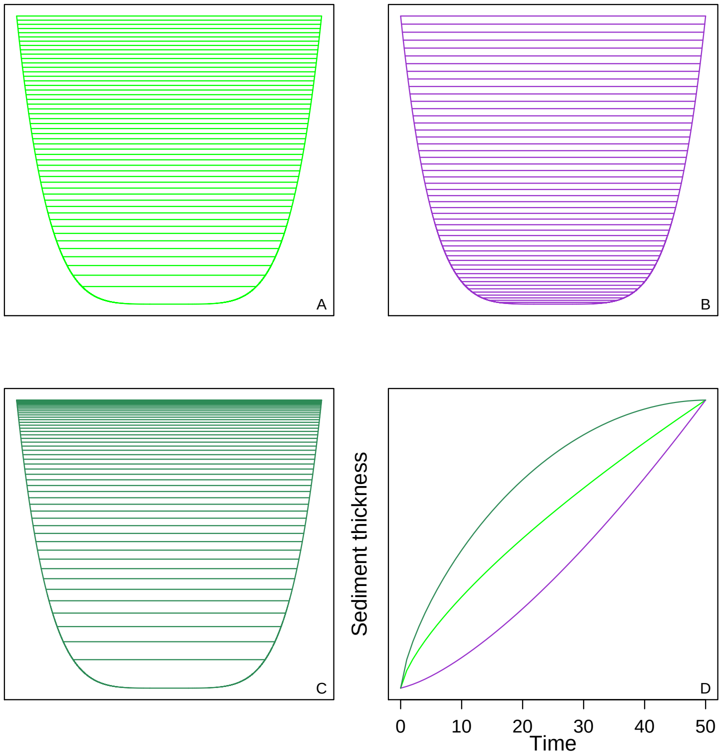

Figure 5 Graphical representation of sediment accumulation in a lake basin of circular surface area and concave profile (obtained by rotating $y = x^5$ for $x > 0$ about the y-axis) over 50 units of time. A: profile of lake with constant sediment input per unit of time. B: profile of lake with sediment input (VSAR) increasing constantly through time. C: profile of lake with sediment input (VSAR) decreasing constantly through time. D: pattern of sediment accumulation at the lake centre through time (DSAR) (curves coloured to correspond to profiles in A, B and C).

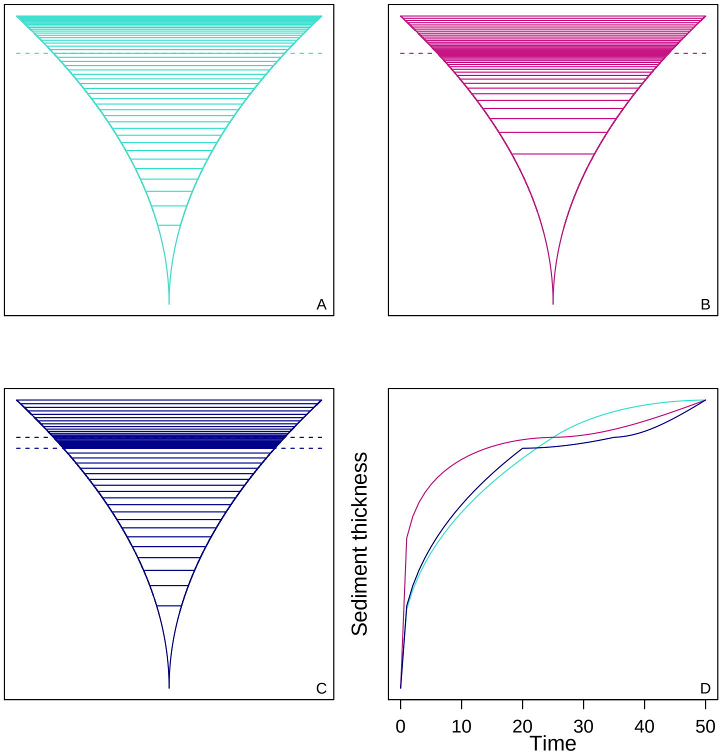

Figure 6 Graphical representation of sediment accumulation in a lake basin of circular surface area and funnel-shaped profile (obtained by rotating $y = x^{0.5}$ for $x > 0$ about the y-axis) over 50 units of time with varying patterns of sediment input. A: profile of lake with pattern of sediment input per time unit divided into two equal length phases: (i) first increasing, then (ii) decreasing. B: profile of lake with pattern of sediment input per time unit (VSAR) divided into two equal length phases: (i) first decreasing, then (ii) increasing. C: profile of lake with pattern of sediment input per unit of time (VSAR) divided into three phases of length 20, 15 and 15 years respectively: (i) first increasing, then (ii) constant, then (iii) increasing. D: pattern of sediment accumulation at the lake centre through time (DSAR) (curves coloured to correspond to profiles in A, B and C). Dashed lines on plots A, B and C correspond to the depths at which changes in sedimentation rate occurred.

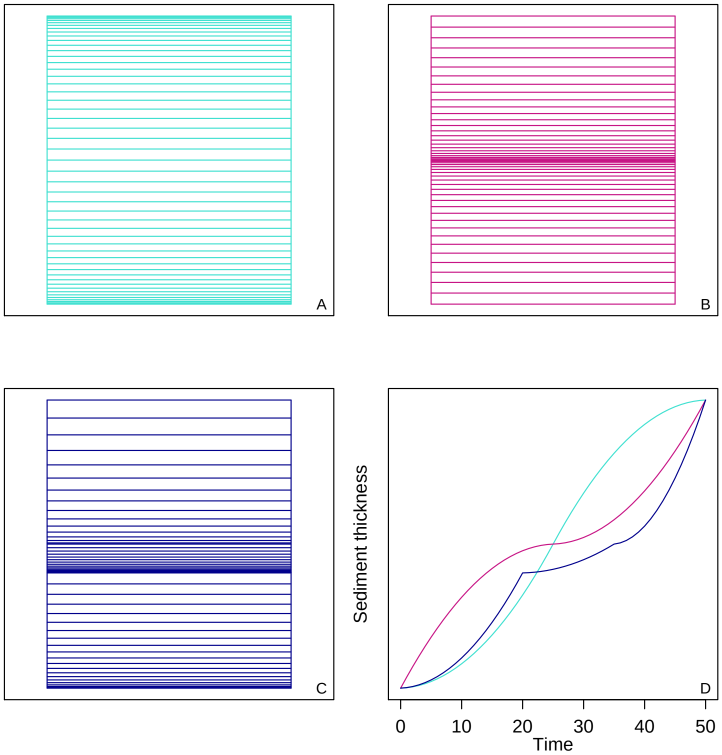

Figure 7 Graphical representation of sediment accumulation in a lake basin of circular surface area and cylindrical profile over 50 units of time with varying patterns of sediment input. A: profile of lake with pattern of sediment input per time unit divided into two equal length phases: (i) first increasing, then (ii) decreasing. B: profile of lake with pattern of sediment input per time unit (VSAR) divided into two equal length phases: (i) first decreasing, then (ii) increasing. C: profile of lake with pattern of sediment input per unit of time (VSAR) divided into three phases of length 20, 15 and 15 years respectively: (i) first increasing, then (ii) constant, then (iii) increasing. D: pattern of sediment accumulation at the lake centre through time (DSAR) (curves coloured to correspond to profiles in A, B and C). Dashed lines on plots A, B and C correspond to the depths at which changes in sedimentation rate occurred.

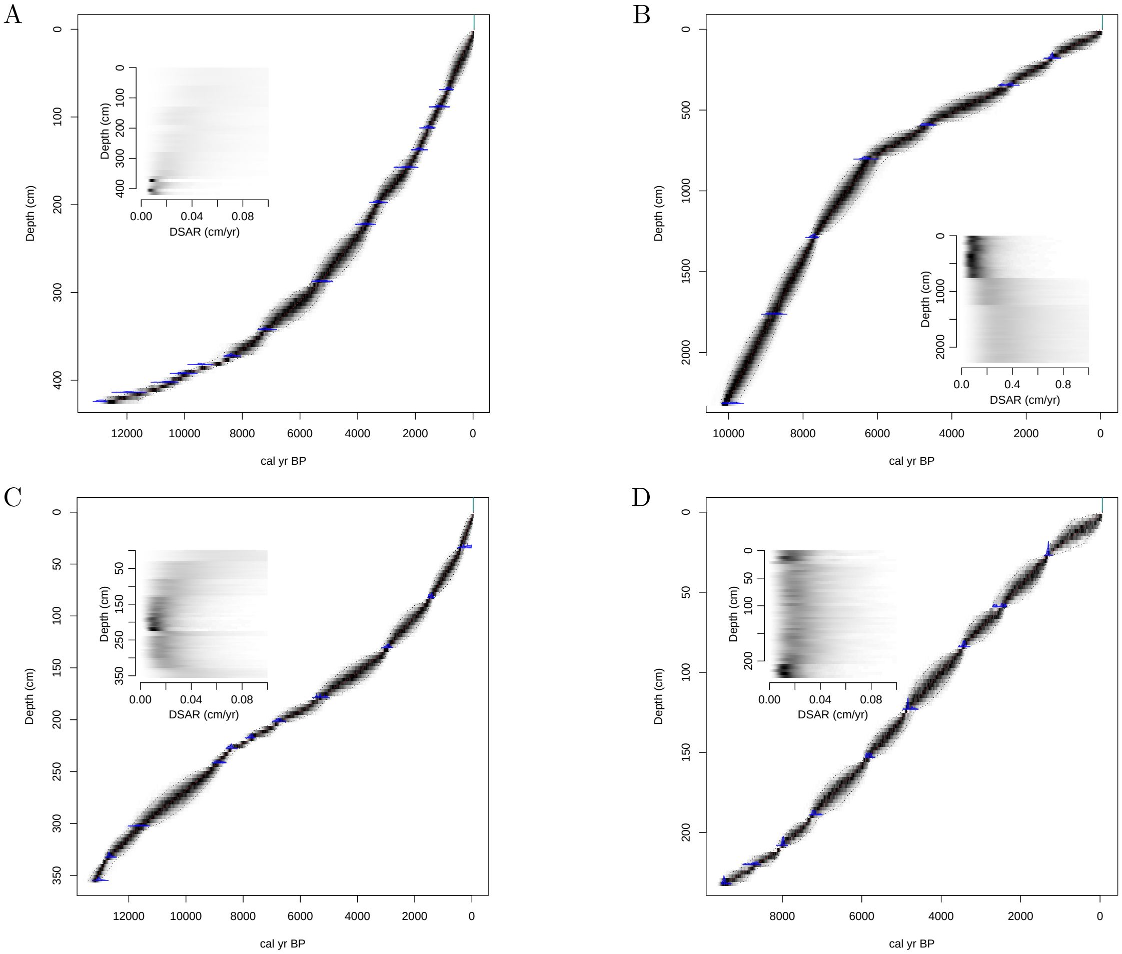

Figure 8 Posterior age-depth models of example cores overlaying the calibrated distributions of the individual radiocarbon dates (blue) and surface known calendar age (blue-green). Red curve shows mean age-depth model and greyscale shows uncertainty (darker grey indicates more secure age). Grey dots indicate the 95% probability intervals for the age depth model. Inset plot shows sediment accumulation rates at the coring point (DSAR) plotted against depth (darker grey shades indicate less uncertainty). A: Kettlehole Pond, Yukon, Canada (Cwynar 1988); B: Tilo, Ethiopia (Telford and Lamb 1999); C: Vestre Øykjamyrtjørn, Norway (Bjune 2005); D: Vikjordvatnet, Norway (Balascio and Bradley 2012). Obtained using Bacon 2.2 (Blaauw and Christen 2011).