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Research paper

Improving age-depth models of fluvio-lacustrine deposits using sedimentary proxies for accumulation rates

P.S.J. Minderhoud [a,*], K.M. Cohen [a,b,c], W.H.J. Toonen [a,b], G. Erkens [b,a], W.Z. Hoek [a]

[a] Department of Physical Geography, Utrecht University, The Netherlands
[b] Department of Applied Geophysics and Geology, Deltares Research Institute, Utrecht, The Netherlands
[c] TNO Geological Survey of The Netherlands, Utrecht, The Netherlands

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ABSTRACT

Lacustrine fills, including those of oxbow lakes in river floodplains, often hold valuable sedimentary and biological proxy records of palaeo-environmental change. Precise dating of accumulated sediments at levels throughout these records is crucial for interpretation and correlation of (proxy) data existing within the fills. Typically, dates are gathered from multiple sampled levels and their results are combined in age-depth models to estimate the ages of events identified *between* the datings. In this paper, a method of age-depth modelling is presented that varies the vertical accumulation rate of the lake fill based on continuous sedimentary data. In between Bayesian calibrated radiocarbon dates, this produces a modified non-linear age-depth relation based on sedimentology rather than linear or spline interpolation.

The method is showcased on a core of an infilled palaeomeander at the floodplain edge of the river Rhine near Rheinberg (Germany). The sequence spans from ~4.7 to 2.9 ka cal BP and consists of 5.5 m of laminated lacustrine, organo-clastic mud, covered by ~1 m of peaty clay. Four radiocarbon dates provide direct dating control, mapping and dating in the wider surroundings provide additional control. The laminated, organo-clastic facies of the oxbow fill contains a record of nearby fluvial-geomorphological activity, including meander reconfiguration events and passage of rare large floods, recognized as fluctuations in coarseness and amount of allochthonous clastic sediment input. Continuous along-core sampling and measurement of loss-on-ignition (LOI) provided a fast way of expressing the variation in clastic sedimentation influx from the nearby river versus autochthonous organic deposition derived from biogenic production in the lake itself. This low-cost sedimentary proxy data feeds into the age-depth modelling. The sedimentology-modelled age-depth relation (re)produces the distinct lithological boundaries in the fill as marked changes in sedimentation rate. Especially the organo-clastic muddy facies subdivides in centennial intervals of relative faster and slower accumulation. For such intervals, sedimentation rates are produced that deviate 10–20% from that in simpler stepped linear age-models. For irregularly laminated muddy intervals of the oxbow fill – from which meaningful sampling for radiocarbon dating is more difficult than from peaty or slowly accumulating organic lake sediments – supplementing spotty radiocarbon sampling with continuous sedimentary proxy data creates more realistic age-depth modelling results.

1. Introduction

Sedimentary records of lacustrine fills from various settings form valuable archives of past environmental change. It is imperative to place the data from such records within the correct timeframe, to enable precise dating of lacustrine stratigraphies and to allow integration with other records (Bronk Ramsey et al., 2014). Doing so often requires a high abundance of dates and age-depth models that provide age estimates between dated levels (e.g. Lohne et al., 2013). In recent years, advanced tools have become available that allow to produce age-depth relations for lake core sequences while incorporating Bayesian statistical techniques (e.g. Blaauw and Christen, 2005; Bronk Ramsey, 2008; Haslett and Parnell, 2008). Reliability of age-depth modelling using such tools

* Corresponding author. P.O. Box 80.115, 3508 TC, Utrecht, The Netherlands.
E-mail address: P.S.J.Minderhoud@uu.nl (P.S.J. Minderhoud).

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depends on the number of dates, and hence, datable material in the record. However, in lacustrine environments that regularly trap amounts of allochthonous sediment, such as lakes in river valleys and floodplains, meaningful dateable organic material is often hard to collect over considerable vertical intervals. For such intervals, age-depth modelling tools typically fall back to assuming linear accumulation (see also Blaauw, 2010: his Table 1). If the lake fills are varved, counting (semi) annual deposition layers provides additional options, (e.g. Schlolaut et al., 2012; Shanahan et al., 2012). Where very distinct sedimentary breaks occur in the fill; (i) sampling for dating as close as possible to the break and; (ii) prescribing this break in the age-depth model is preferable, to bound the to-be-modelled interval or to use it as a knick point (Bronk Ramsey, 2008). The more gradual the sedimentary variations are, the more difficult and arbitrary established age-modelling solutions become.

In irregularly laminated silty mud intervals of oxbow lake fills, deploying linear models between sparse radiocarbon dates at just a few vertical positions, produces smooth age-depth relations, which are unrealistic from setting and sedimentological perspectives. In large parts, this is due to not using the sedimentary information in the core to the full potential. Where sedimentology of the core itself shows a variability that directly relates to accelerations and decelerations in rates of vertical accumulation of oxbow fill, this information should feed into the age model. Where such information can be routinely gathered at higher resolution than the sampling for dating, descriptive sedimentary data (i.e. along-core measurements describing variations in percentage organics, and/or grain size, and/or lamination thickness) can serve as proxy data for variations in sedimentation rate. Examples of such approaches are found in many sedimentary environments, ranging from alpine lakes (allochthonous organics: e.g. Fuentes et al., 2013), to varved lakes (lamination thickness: e.g. Brauer et al., 1999) and oxbow lakes (organic content and grain size: Toonen et al., 2012, 2015), to deep marine environments (turbidity activity: Toucanne et al., 2008), to long-term sedimentary accumulation (cyclo-stratigraphic facies alternations: De Boer and Smith, 2009). In aeolian deposits Vandenberghe et al. (1997) used grain-size information as input to age-depth modelling within glacial accumulation stages, between interglacial soil horizons in a Central China loess sequence, with direct grain-size measurements used as the continuous sedimentary proxy recording variation in accumulation rates. In the organo-clastic fluvial-lacustrine case, the proportion of clastics versus organics is just such a sedimentary proxy for variation of accumulation rates, as this paper explores.

We present a spreadsheet method for constructing non-linear modified age-depth models, which incorporates variations in sedimentation rates of siliciclastic and organic material in fluvio-lacustrine environments. In this environment, increased rates of deposition of siliciclastic material in these lake basins is event-based. Gross amounts of siliclastics are delivered only when the river floods. How often this typically happens changes through time, predominantly because the active river migrates and changes proximity to the site (described in further sections of the paper). Therefore, relatively clastic subintervals have higher sedimentation rates than subintervals dominated by autochtonous lake production, which forms the organic background accumulation and is assumed to accumulate at a more or less constant rate over time (compared to clastic influxes). The age-depth model is ‘corrected’ using a continuous sampled loss-on-ignition record as the sedimentary proxy data signaling accelerating and decelerating vertical aggradation.

We developed the method using a Lower Rhine valley oxbow fill of Middle Holocene age (Fig. 1). The site was initially visited for collecting a channel abandonment date from the base (Erkens, 2009). The ~1750-year long record that the oxbow fill

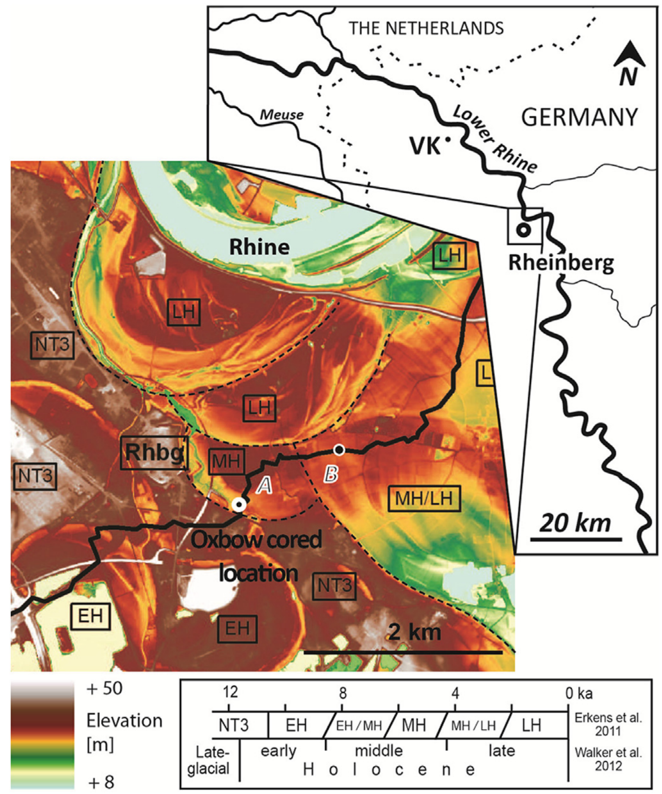

Fig. 1. Location of the Rheinberg palaeochannel (A) and its immediate successor (B) in Nordrhein Westfalen, Germany. Dots show sample core locations and the dashed lines mark scarps of former Rhine meanders. Rhbg = village of Rheinberg located on the Lateglacial Niederterrase 3 (NT3); EH, MH, and LH = Early, Middle, and Late Holocene; VK = (Vossekuhl) slackwater site of a millennial flood dated to ~4.7 ka (Toonen et al., 2013). Annotated LiDAR imagery after Erkens et al. (2011).

sedimentary sequence appeared to hold, was exploited for reconstruction of further events of meander reconfiguration and periodical variations in recurrence of larger floods (Toonen, 2013). The oxbow fill accumulated over the period ~4.7 to 2.9 ka cal BP, when prehistoric deforestation first began to affect the dynamics of the Rhine drainage system (e.g., Erkens et al., 2006; Hoffmann et al., 2007, 2009), and a period believed to have seen climatic variation (e.g., the 4.2 ka event) during the Middle to Late Holocene transition (Walker et al., 2012).

2. Sedimentology of oxbow fills

In lowland rivers of meandering style and mixed sediment load, palaeochannels at moderate distance away from active channels accumulate organo-clastic deposits in subaqueous environments of oxbow lakes (Allen, 1965; Shields and Abt, 1989; Toonen et al., 2012; Lewin and Ashworth, 2014). Once disconnected from the active channel, the deepest part of a newly formed oxbow lake matches the former channel's bend thalweg depth (6–10 m in the case of the Lower Rhine). Close to the meander cut-off location, relatively coarse sediment accumulates as the outcome of initial cut-off and plugging processes, which usually causes rapid shallowing of the oxbow entrance within decades following cut-off (Dieras et al., 2013; Hooke, 1995). Further into the oxbow, shallowing is typically much less (Citterio and Piégay, 2009) and if the cut-off process terminated flow through the former meander abruptly, it is only subtly different from overlying deposits where the oxbow lake was deepest. It is not uncommon to encounter cm-