Quaternary International 401 (2016) 174–183

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

An automated algorithm for dating annually laminated sediments using X-ray radiographic images, with applications to Lake Van (Turkey), Lake Nautajarvi (Finland) and Byfjorden (Sweden)

Emre Damcı [a, b, *], M. Namık Çağatay [a, c]

[a] Eastern Mediterranean Center for Oceanography and Limnology (EMCOL), Istanbul Teknik Üniversitesi, 34469, Maslak, Istanbul, Turkey
[b] Eurasia Institute of Earth Science, Istanbul Teknik Üniversitesi, 34469, Maslak, Istanbul, Turkey
[c] Department of Geological Engineering, Istanbul Teknik Üniversitesi, 34469, Maslak, Istanbul, Turkey

ARTICLE INFO

Article history:
Available online 30 May 2015

Keywords:
Laminated sediments
Varve counting
Radiography
Paleolimnology
Paleoceanography
Dating

ABSTRACT

Annually laminated (varved) sediments in marine and lake basins are important archives for paleoenvironmental and paleoclimatic reconstructions, especially with their property to provide a continuous chronology. In this study we introduce a new approach for counting laminae using both digital and analogue X-ray radiographic images. The requirement for the method is that the resolution of the image is higher than the minimum lamina thickness, so that the measurement interval should be at least one third of the minimum lamina thickness. In our method, 8-bit or 16-bit grey scale radiographic images are scaled to grey-scale values between 0 and 1, and every maximum and minimum peaks corresponding to seasonal lamination are defined along the sediment core. The algorithm counts laminae rather than varves, thus allowing control on estimation of more reliable age models. Detected peaks are summed cumulatively along the core length, using a step determined by the annual lamina number of the varve.

Using the algorithm, we provide test examples from the varved sediments of the Lake Nautajarvi in Finland, Byfjorden in Sweden and Lake Van in eastern Turkey, and compare our results with previously dated levels in the cores. There are good agreements between the varve counting results of our study and the previous studies, except for the ages from the lower part of the Lake Van core corresponding to a time interval between ca. 7000 and 8000 BP, for which there is ca 1000 year difference between the two sets of results. This difference might be the result of under-counting of varves in the previous studies.

1. Introduction

Annually laminated (varved sediments) sediments commonly occur in anoxic silled marine basins (e.g., Baltic Sea) and in alkaline (e.g., Lake Van), anoxic and some oxic lakes (e.g., Kempe and Degens, 1978; Sturm and Matter, 1978; Sturm, 1979; Kempe et al., 2002; Ojala et al., 2012; Stockhecke et al., 2014). Such sediments are important archives for paleoenvironmental reconstructions, as they also provide a robust chronology based on varve counting. However, varve counting is a tedious and time-consuming process, depending on the method employed but considered to be the most important step in the construction of varve chronologies. There are several methods of varve counting, which include the use of X-ray radiography (Hamblin, 1962; Schimmelmann and Lange, 1996), digital optical images (Shaaf and Thurow, 1994), and thin section petrography (Zolitschka, 1996). Some methods such as scanning electron microscopy (SEM) coupled with an energy dispersive X-ray fluorescence (XRF) spectrophotometry and petrographic thin section analyses are common in generating data on interannual variability of the composition of various laminae forming a varve (Goldstein et al., 1992; Dean et al., 1999).

An annually formed varve usually consists of two or more laminae, each of which is composed of various proportions of biogenic and clastic mineral components which are deposited during an annual cycle. Varve counting may involve errors, usually because of the absence, or multiple occurrences of biologically originated laminae in some year's annual varve structure, and/or interruptions due to event sedimentation (Lotter and Lemcke, 1999; Zolitschka, 2007; Ojala et al., 2012). A world-wide varve data base

* Corresponding author. Eastern Mediterranean Center for Oceanography and Limnology (EMCOL), Istanbul Teknik Üniversitesi, 34469, Maslak, Istanbul, Turkey.
E-mail addresses: damci@itu.edu.tr (E. Damcı), cagatay@itu.edu.tr (M.N. Çağatay).

http://dx.doi.org/10.1016/j.quaint.2015.05.007
1040-6182/

provides error estimations between 1 and 3% for their varve chronologies (Ojala et al., 2012).

Automated varve counting and measuring software packages have been previously developed (Varem-Sanders and Campbell, 1996; Conner et al., 2000; Francus et al., 2002; Meyer et al., 2006; Weber et al., 2010; Ndiaye et al., 2012). For example, Francus et al. (2002) used an algorithm to count laminae from digital microphotographs of petrographic thin-sections. Counting algorithms are generally used with optical images of cores. X-ray radiography of sediment cores provides a grey scale image of sediment's internal structure including laminations, based on differences in the density of the laminae. Distinct density differences are present in varve structures involving clastic, biogenic (shell and skeletal material), carbonate, and organic carbon-rich laminae. Even in the case of clay and calcareous types of varves (Zolitschka, 2007), density differences are commonly observed in the radiographic images because of the differences in the density, porosity and relative proportion of different clay and carbonate minerals making up the seasonal laminae (Ojala and Francus, 2002; Zolitschka et al., 2015).

A few radiographic image analysis algorithms were developed for the tree-ring count which are not as complicated as the varve structures (e.g., Pilcher et al., 1984; Varem-Sanders and Campbell, 1996). Radiographic images provide a rapid and non-destructive tool for counting the varves for age dating purposes. However, previously developed varve counting methods are generally complicated and have some problems with error estimation. All of these methods compare their results with independently determined reference ages. Hence, the error is determined at a given point, using a best fit single line or a statistical confidence band along the core length. Such methods ignore the common systematic errors in varve counting, which are cumulative and increase downcore. Many previously published studies do not report any errors in varve counting. For example only 57% of the published records from a varve data base of 108 records provided error estimations (Ojala et al., 2012). Moreover, most of these studies do not provide details on the methods of error estimation.

In this study we present an algorithm to count laminae and varves using analog and digital X-ray radiographic images. The algorithm is a fast, reliable, user friendly with an ability to make more realistic downcore cumulative error interval estimation. Our method uses the whole width of the radiographic image along the core length, instead of limited line of analysis. Counting the laminae for a number of analytical paths (lines) along the core radiographic image provides more reliable results and allows for calculation of error involved in automated lamina/varve counting. For our method, we used radiographic images of previously dated sediment cores from Lake Nautajarvi in Finland (Ojala and Tiljander, 2003), Byfjorden fjord in Sweden (Axelsson, 2002) and digital X-ray radiographic images of a core from Lake Van, eastern Turkey (Fig. 1).

2. Study sites

Lake Nautajarvi is located in central Finland. It has a maximum depth of 20 m and area of 0.45 km^2 (Fig. 1a). Its catchment consists of easily erodible fine-grained clastic material, silt or clay. The lake basin accumulates sediments with clastic-organic varves (Ojala and Tiljander, 2003; Ojala et al., 2013). Each varve consists of three laminae; a) a detrital mineral-rich lamina deposited during spring floods, b) a particulate organic material-rich lamina accumulated during summer to autumn, and c) a thin dark-coloured organic-rich lamina that is deposited under the ice cover during winter

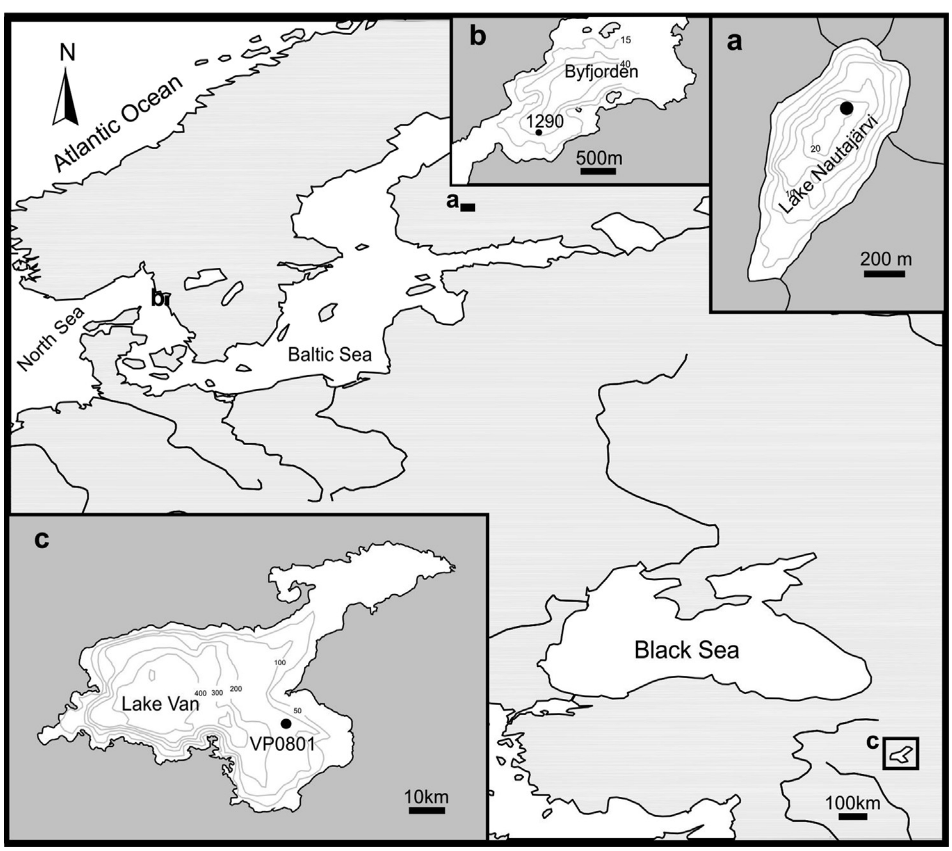

Fig. 1. Location of cores used for testing the varve count for age dating: a) core from Lake Nautajarvi (Ojala and Tiljander, 2003), b) core 1290 from Byfjorden (Axelsson, 2002) and c) core VP0801 form Lake Van (Makaroğlu, 2011).