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Semi-automated detection of annual laminae (varves) in lake sediments using a fuzzy logic algorithm

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A B S T R A C T

Annual laminae (varves) in lake sediments are typically visually identified, measured and counted, although numerous attempts have been made to automate this process. The reason for the failure of most of these automated algorithms for varve counting is the complexity of the seasonal laminations, typically rich in lateral facies variations and internal heterogeneities. In the manual counting of varves, the investigator acquired and interpreted flexible numbers of complex decision criteria to understand whether a particular simple lamination is a varve or not. Fuzzy systems simulate the flexible decision making process in a computer by introducing a smooth transition between true varve and false varve. In our investigation, we use an adaptive neuro fuzzy inference system (ANFIS) to detect varves on the basis of a digital image of the sediment. The results of the application of the ANFIS to laminated sediments from the Meerfelder Maar (Eifel, Germany) and from a landslide-dammed lake in the Quebrada de Cafayate of Argentina are compared with manual varve counts and possible reasons for the differences are discussed.

1. Introduction

Annually laminated (varved) sediments represent high-resolution archives of past climate change (Zolitschka, 1996; Lamoureux, 2001; Brauer, 2004; Veski et al., 2004; Brauer et al., 2008). An annual chronology of climate-driven environmental shifts requires the investigation of sediment structures to establish the seasonal characteristics of the sediment (Anderson, 1996), in particular, to distinguish between annual and sub-annual layering (Brauer and Casanova, 2001). The traditional approach to prove sediment laminae as varves is to correlate the microfacial variability within single lamination with physical, chemical, and biological cycles in the annually laminated archives of marine and lacustrine sediments (Lotter and Lemke, 1999). Alternatively, the cross correlation of counts with radiometric dates helps to confirm that the laminae patterns are of annual origin (e.g., Ojala et al., 2012). However, the process of varve counting and the measurement of varve thicknesses by means of microscopic techniques or high-resolution geochemical analyses (such as XRF, ICP MS or AES techniques) still remains a time-consuming and costly task (Francus et al., 2002; Brauer and Dulski, 2010). The quality of manual varve counts is also limited by the specific quality of the images used for counting (e.g., Ojala et al., 2012). In such cases automated algorithms may help in detecting possible errors in the process of varve counting.

Numerous efforts to identify and model the annual or sub-annual layering on sediment surfaces and petrographic thin sections have been made to automate varve counting (Schaaf and Thurow, 1994; Zolitschka, 1996b; Weber et al., 2010). Image analysis algorithms provide satisfactory results for sediments showing regular and simple alternations in sediment composition (Zolitschka, 1996b). Unfortunately, annually laminated sediments are typically rich in lateral facies variations and internal heterogeneities that hamper accurate chronologies based on automatically varve counting (Lotter and Lemke, 1999; Weber et al., 2010; Kinder et al., 2013).

Because no versatile and reliable automated systems for varve counting are currently available (Francus et al., 2002; Weber et al., 2010), the most promising algorithms include the combination of two or more independent methods to detect varves. One of the most recent efforts to perform fully automated varve counting based on image analysis provides maximum count, zero-crossing and frequency truncation techniques for annually laminae investigation and is available in the software package *BMPix tool* (Weber et al., 2010). An additional example that is highly successful, combines microscopic thin section counts with red, green, blue (RGB) scans, varve microfacies analyses and μ-XRF element scans (Brauer and Dulski, 2010). Others used assisted tools for manual counting of automatically retrieved marks such as lamination boundaries on digital images of thin sections of the sediments. In order to speed up varve counting and measurements of layer thicknesses, computer assisted algorithms have the ability to improve the accuracy of the detection and counting process (e.g., Francus et al., 2002; Weber et al., 2010).

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Operator assisted methods for classification between annual and/or sub-annual lamination are impractical for large amounts of data and potentially contain a high noise level that can lead to serious inaccuracies in the varved records (Ojala et al., 2012). It has been shown that repeated-counting of microscopic thin section images helps to reduce these errors especially in the case of manual varve counting. An alternative approach to reduce noise in manually detected varves is the use of computer aided techniques of image analysis. Many image analysis algorithms cannot work well in a noisy environment, as described above. Therefore, automating varve counts involves highly sophisticated mathematical algorithms, including pattern recognition. As an example for such an algorithm, neural systems have the capability to learn any patterns contained in highly complex sediment sequences. The purpose of such networks is to detect structural properties of the input space and adapt their internal structures to those properties (Ultsch, 1993; Francus et al., 2002).

In our approach, we use fuzzy systems as another example of such a mathematical algorithm to detect varves in digital images of sediments and to make them available for subsequent automated varve counts. The application of fuzzy systems has shown to be particularly useful where diffuse information of complex systems is to be described with models. By using fuzzy systems, it is possible to digitally model experiences and information, which can be described verbally by humans,

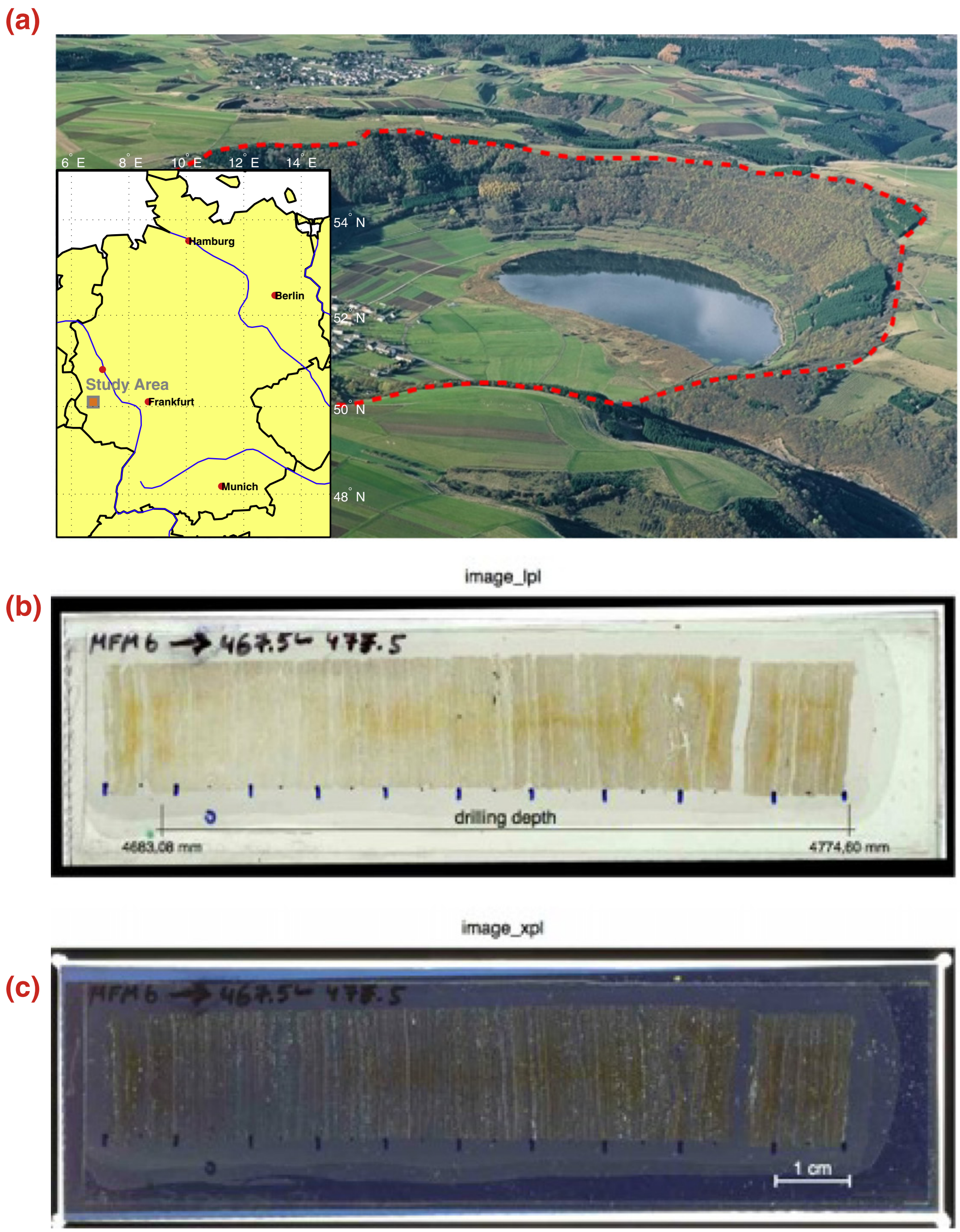

Fig. 1. (a) Location of the Meerfelder Maar—marked as *Study Area* in the inset box, and aerial photo of the maar lake and its catchment—indicated by a red dashed line (adopted and modified after Martin-Puertas et al., 2012) (photo courtesy of Tourist Information Manderscheid). Thin section image with (b) plain polarized light and (c) crossed polarizers showing laminated sediment sequence (468–477 cm core depth) (Rach, 2010).