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Extracting paleoclimate signals from sediment laminae: An automated 2-D image processing method

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ABSTRACT

Lake sediments commonly contain laminations and the occurrence and quantitative attributes of these microstrata contain signals of their depositional environment, limnological conditions, and past climate. However, the identification and measurement of laminae and their attributes remains a largely semi-manual process that is tedious, labor intensive, but subject to human error. Here, we present a method to automatically measure and accurately extract lamina properties from sediment core images. This method is comprised of four major components: (1) image enhancement that includes noise reduction and contrast enhancement to improve signal-to-background ratio and resolution of laminae; (2) identification of 1-D laminae for a user-chosen area in an image; (3) laminae connectivity analyses on the 1-D laminae to obtain a lamina stratigraphy; and (4) extraction and retrieval of the primary and derived lamination stratigraphic data. Sediment core images from Lake Hitchcock and Lake Bosumtwi were used for algorithm development and testing. Our experiments show a complete match between laminae produced by the software and manual process for images from Lake Hitchcock. Quantitative comparisons reveal an insignificant discrepancy in the number of laminae identified automatically by the software and manually by researchers, and in over 90% of the cases the position mismatch of individual laminae is less than one pixel between the software and the manual method for the experimental images from Lake Bosumtwi.

1. Introduction

Sediment laminations are primary sedimentary features that preserve records of deposition of sub-annual, annual, and multi-year events. The nature of sediment laminations provides information for reconstruction of depositional and climatic histories on annual, decadal, centennial, and millennial time scales (Alley et al., 1999; Breckenridge, 2007; Desprat et al., 2009; Hofmann et al., 2003; Lamoureux et al., 2001; Nederbragt and Thurow, 2001; Sander et al., 2002; Tiljander, 2005; Von Rad et al., 2006). Although laminae may form by a variety of mechanisms that produce different physical (e.g., grain size) and/or chemical attributes (e.g., mineralogy and/or organic content) (Anderson, 1964; Kemp, 1996), they share a common visual characteristic—the alternation of light and dark bands. This characteristic is used to define laminae and their thicknesses from digital images.

Sediment lamination studies have a long history (Anderson, 1964), but the identification and measurement of lamina attributes remains primarily a manual or semi-manual process due to the lack of effective automated processing tools (Francus et al., 2002; Francus and Nobert, 2010; Meyer et al., 2006; Oksanen et al., 2002; Rupf and Radons, 2004; Weber et al., 2010). Inevitably, manual or semi-manual data acquisition is subjective and error-prone (Zolitschka, 1998), and the tedious and labor intensive nature of manual lamina counting and thickness measurement limits the application of these approaches to relatively short depositional records. The development of an automated technique has particular application to analyses of long cores such as those currently acquired in many new scientific drilling programs.

In the last two decades, researchers and software developers have attempted to develop software tools that could permit the efficient and accurate processing of images of laminated sediment profiles (Francus et al., 2002; Francus and Nobert, 2010; Katsuta et al., 2003; Meyer et al., 2006; Rupf and Radons, 2004; Weber et al., 2010). Francus et al. (2002) developed an algorithm to aid in varve counting and measurement from thin-sections. Rupf and Radons (2004) described four automated approaches for the detection of lamina based on 1-D grey-scale vectors. Meyer et al. (2006) describe a commercial software package (WinGeol) that allows for interactive interpretation and measurement of laminae in 1-D profiles. These approaches share a common shortcoming—they process 1-D image data which are inherently noise-prone and subjected to local bias. Katsuta et al. (2003) describe a 2-D method of image

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processing for retrieving lamination data. As pointed out by Rupf and Radons (2004), the Katsuta algorithm was promising, but quality of the input image has to be excellent, which prevents the application of their method to most laminated sediment records. Weber et al. (2010) developed tools for automated laminae recognition and counting, and used these tools to process glacial varves from Antarctic marine sediments. This tool set is developed under MS Excel/VBA, which has inherent limitations.

Here, we present a true 2-D batch method and software named "LA-2D" that identifies and measures laminations in digital images. The LA-2D program includes four major components: (1) an image enhancement component that implements a multi-pass moving average filter for noise reduction, and a sectional contrast enhancement for improving the signal to noise ratio in the vertical direction; (2) identification and measurement of 1-D laminae that implements an optimal fit algorithm to identify 1-D laminae and their boundaries; (3) 2-D lamina connectivity analyses which include image blob analyses and lamina connectivity analyses to obtain the best representative lamina stratigraphy; and (4) a data extraction and retrieval component that is able to retrieve and disseminate various datasets of lamina stratigraphy.

2. General characteristics of digital imagery of sediment cores

Digital images of sediment cores are widely available and used for reconstruction of depositional environments, past limnological conditions, and climate history. In this study, we use sediment core images from two lakes for our algorithm development and software testing: Lake Hitchcock in Massachusetts, USA, and Lake Bosumtwi in Ghana. These two image sets were chosen because they represent end members of laminated sediment core image quality and characteristics. Each image from Lake Hitchcock was acquired from two-foot long sediment core sections, and laminae are typical lake varves (Ridge, 2008a). The visual characteristics of these images are relatively uniform across the width of each core section; laminae boundaries are parallel in the horizontal direction, and the thicknesses of individual lamina ranges from several millimeters to tens of centimeters. Color contrasts between dark and light laminae are obvious and distinct (Fig. 1). Dark laminae, usually $>90\%$ clay, are visually homogeneous products of winter deposition. Light laminae, typically a series of micrograded units of mostly silt with minor amounts of fine sand and clay, consist of several secondary laminae that accumulated during multiple summer depositional events (Ridge, 2008a). The transitions from winter to summer laminae are sharp, but transitions from summer to winter laminae are often gradual (Ridge, 2008b). The major challenges in processing these images are to distinguish laminae that are formed by multiple summer depositional events from those that are the semi-annual depositions, and to accurately identify lamina boundaries between summer and winter deposits which are often gradual.

Sediment core images from Lake Bosumtwi (Fig. 2) are more complicated than those from Lake Hitchcock. A full-length sediment core section is 1.5 m long and represents about 3700 years/meter of deposition on average based on radiometric ages (Koeberl et al., 2005; Shanahan et al., 2012). These images were acquired by a line scan camera with resolutions of either 10 pixels/mm or 20 pixels/mm. Visual properties and features of laminations are often variable within an image. Colors may vary from very bright to very dark, and contrasts between dark and light laminae range from faint to very distinct in the same image (Fig. 2). These features impose a challenge for using a threshold value for lamina identification: if a threshold value is too small, it may lead to extra laminae which could be internal variations within a lamina; if a threshold value is too large, it may result in missing many subtle laminae. Meanwhile, lamina thicknesses are highly variable from one (equivalent to 0.05 or 0.1 mm) to tens of pixels (several millimeters) within individual images, and lamina boundaries are rarely straight or sharp. These characteristics require algorithms of image enhancement to be applicable and yet effective to a large spectrum of lamina thickness and boundary conditions.

Both image sets, however, share essential elements of laminated sediment profiles. The most obvious yet the most essential feature is their dimensionality. In the horizontal direction (for illustration convenience, we use y-axis for the horizontal direction and x-axis for vertical direction in all figures except Fig. 10), the dominant feature is that individual laminae may extend entirely or partially across the image. Variances in color or irregular lamina boundaries are predominantly a consequence of local biases and noise. In contrast, alternating dark and light laminae are the expected pattern in the vertical direction, and thicknesses of these laminae may vary due to variations of depositional rates or changes in depositional environment. These characteristics have several crucial implications for lamina

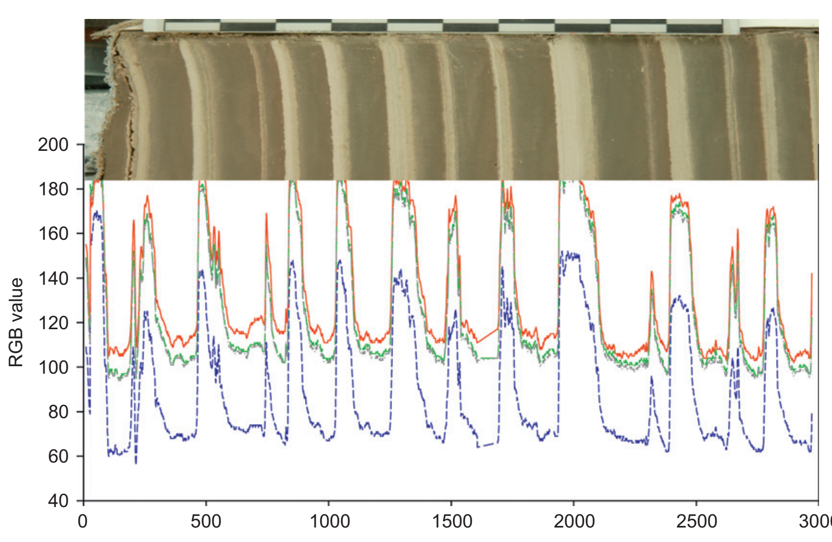

Fig. 1. An original core image and its RGB curves from Lake Hitchcock, Massachusetts, USA. The scale is cm.