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Spatial and temporal variability in sedimentological and geochemical properties of sediments from an anoxic crater lake in West Africa: Implications for paleoenvironmental reconstructions

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ABSTRACT

The physical, inorganic and organic geochemical and stable isotopic characteristics of lacustrine sediments can provide valuable insights into past environmental changes, provided that the environmental controls on these characteristics are well understood. In the present study, a set of 155 modern vegetation, catchment soil, river sediments and lake surface sediment samples are used to characterize the spatial patterns of TOC, TN, C/N ratios, stable isotope, major element, and particle size distributions within Lake Bosumtwi, a meromictic crater lake in West Africa. Spatial variations in sediment characteristics are strongly correlated with depth and distance from shore, reflecting the dominant influence of lake level on the relative proportions of littoral and pelagic depositional systems and their impact on the physical and geochemical properties of lacustrine sediments. This is supported by a principal component analysis, which indicates that 65% of the variance in the dataset is explained by depth-related variability in the sedimentary components. Variations in sedimentary organic matter reflect the combined influences of productivity, preservation and the relative proportions of aquatic and terrestrial organic matter sources. Grain size and Si content are dominantly influenced by the delivery of clastic materials from the watershed to the lake, whereas Fe and Ca appear to be most strongly influenced by the delivery of reduced metals and nutrients from the anoxic hypolimnion to the surface. With the exception of grain size, all of the sediment parameters record synchronous century-scale variability over the past ~2.5 ka, consistent with independent evidence for changes in lake level. However, the magnitude of changes in sediment characteristics differs, reflecting different sensitivities to water depth, particularly in the deepest part of the lake basin where the sediment cores were collected. However, even the parameters with the most linear and strongly significant relationships with depth (e.g., TOC, TN) significantly overestimate the magnitude of lake level changes, suggesting that these parameters may be best suited to qualitative paleolake level reconstructions. Over the last 2 centuries, changes in C/N and $\delta^{13}C$ became decoupled from the other geochemical proxies and the inferred rise in lake level. We hypothesize that this reflects the influence of anthropogenic land use change on the composition of terrestrial organic matter sources contributing to the lake. This result highlights the potential difficulties in reconstructing past environmental changes from indirect proxy measurements when those proxies may be subject to multiple varying controls.

1. Introduction

Lake sediments contain unique and potentially valuable archives of paleoenvironmental conditions through their sedimentological, biological and geochemical characteristics. A wide variety of techniques are now commonly employed in paleolimnology, including: pollen (Birks and Gordon, 1985; Berglund and Ralska-Jasiewiczowa, 1986; Bennett and Willis, 2001), aquatic biological indicators (Battarbee et al., 2001; Holmes, 2001; Walker, 2001), bulk organic and carbonate

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geochemistry and stable isotope analysis (Ito, 2001; Meyers and Teranes, 2001; Talbot, 2001; Leng et al., 2005), inorganic geochemistry (Engstrom and Wright, 1984; Boyle, 2001), textural characteristics (Sly, 1978; Anadon et al., 1991; Talbot and Allen, 1996), magnetics (Thompson et al., 1975; Dearing, 1999; Sandgren and Snowball, 2001) and most recently molecular biomarkers (Eglinton et al., 1993; Meyers, 1997; Castañeda and Schouten, 2011). While inferences from some of the biological and stable isotope proxies are independently calibrated using training sets or experiments, others such as changes in bulk organic and inorganic geochemistry depend significantly on basin characteristics. Inferences based on these bulk properties require a more detailed understanding of sediment source, transport, deposition and preservation and how these factors might be influenced by changes in lake environment or climate.

Here we use a dataset of modern sediment, particulate and vegetation samples to characterize the processes influencing the sediments from Lake Bosumtwi, an anoxic crater lake in West Africa (6°30′N, 1°25′W). Previous studies have demonstrated that Lake Bosumtwi contains a remarkable record of past climate and paleoenvironmental changes through the physical, geochemical and stable isotope characteristics of its sediment record (Talbot and Johannessen, 1992; Peck et al., 2004; Shanahan et al., 2009). This work provides an improved understanding of the controls on these signals and their interpretation. Then we use these relationships to examine the changes in lake sediment characteristics over the last ~2.5 millennia. These data provide new insights into the response of Lake Bosumtwi to recent climate and anthropogenic influences.

2. Methods

2.1. Site location and setting

Lake Bosumtwi fills a medium sized meteorite impact crater in Ghana, West Africa, which formed at 1.07 Ma (Koeberl et al., 1998) (Fig. 1). The lake is currently 8 km in diameter and 75 m in depth and is surrounded by a steep crater rim ca. 110 m above the modern lake surface. Seismic data indicates that the crater contains a well-defined central uplift, which is now covered by ca. 200 m of lacustrine fill deposited in the basin since the impact (Scholz et al., 2002). The lake is hydrologically closed, and last overflowed sometime before 3000–5000 yr BP (Shanahan et al., 2006; Shanahan et al., 2007a). This has resulted in the gradual accumulation of dissolved solids and slightly brackish (conductivity 1150 μS cm^{-1}) and alkaline (pH = 9.0) water (Turner et al., 1996b) (Fig. 2). Lake water temperatures range from 27.5–32.2 °C at the surface to 26.6 °C at the bottom (Turner et al., 1996a) with a well-developed thermocline at 15 m. This inhibits deep mixing of the water column and results in permanently anoxic bottom waters and the preservation of annual sediment laminations (Shanahan et al., 2007b) (Fig. 2). Waters in the hypolimnion are enriched in nutrients as a result of water column stratification. Mixed layer phosphorous (3 μmol L^{-1}) and nitrogen (30 μmol L^{-1}) concentrations are not limiting, though silica appears to be (10–13 μmol L^{-1}), and is likely responsible for low diatom productivity and preservation.

The climate of Lake Bosumtwi is humid, receiving ca. 1260 mm of precipitation annually (Shanahan et al., 2007a). Most of this rainfall

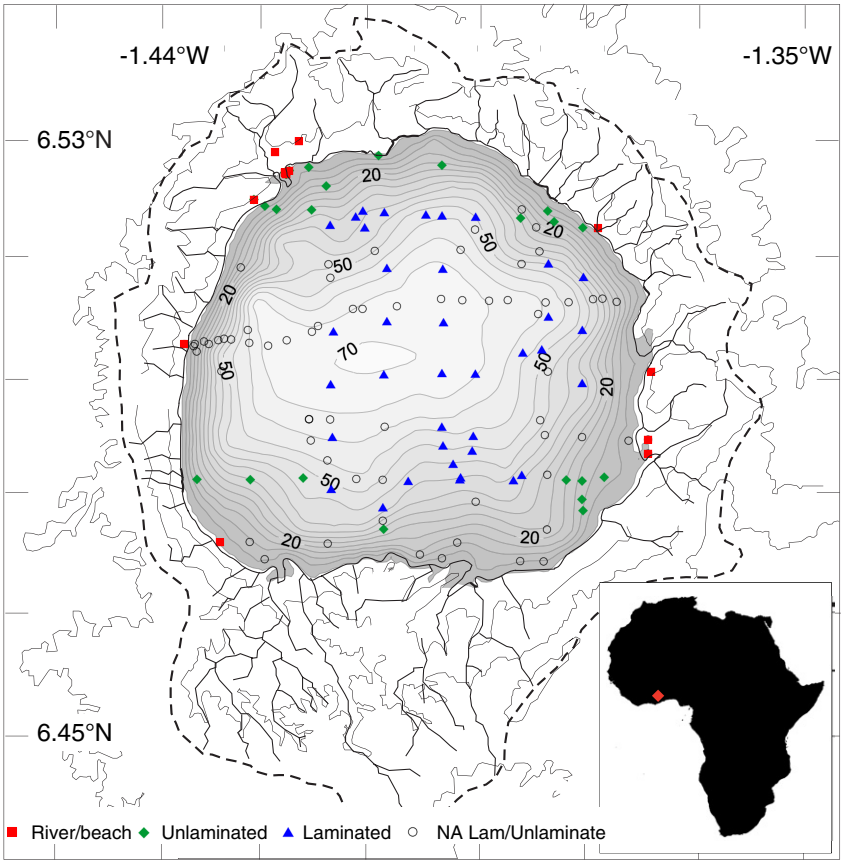

Fig. 1. Bathymetry (contours, shading) and surface sample locations at Lake Bosumtwi, Ghana. 10-meter depth contours were produced by gridding the bathymetric data of Scholz et al. (2007). Samples were collected from rivers and beaches (■) and at locations across the lake basin. Lake surface sediment samples were identified in the field as laminated (▲), or unlaminated (◆). For some samples, the presence/absence of laminations was either indeterminate or not recorded (○). Inset: location of Lake Bosumtwi in West Africa.