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Research paper

Age models for long lacustrine sediment records using multiple dating approaches – An example from Lake Bosumtwi, Ghana

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A B S T R A C T

The continuous 300-m long drill cores obtained from Lake Bosumtwi, Ghana represent one of the longest, continuous lacustrine sequences obtained from an extant lake, and contain an unprecedented record of late Quaternary climate change in West Africa. However, one of the main challenges associated with generating long paleoclimate time series from terrestrial records such as this is the development of accurate age-depth relationships because unlike marine records, lacustrine sequences cannot be tuned to global ice volume records via $\delta^{18}O$ stratigraphy. The Lake Bosumtwi record thus offers an excellent case study for examining the potential and the challenges associated with different geochronological techniques in lacustrine systems. In the present study, we use a combination of radiocarbon, optically stimulated luminescence and U-series dating and paleomagnetic excursions to generate a chronology for the upper ca. 150 ka of sedimentation at Lake Bosumtwi and employ a Bayesian approach to generate a continuous age-depth relationship. The resultant chronology is then used to test the effectiveness of tuning of an environmental magnetic proxy for dust against a well-dated record of high latitude dust. Our approach highlights the advantages of using multiple dating approaches, and the dangers of relying on too few age constraints when dating long sedimentary sequences. However, the excellent agreement between the different approaches over most of the record suggest that well-constrained age-depth models for long sedimentary sequences can be produced using this combination of approaches. Furthermore, our data provide support for extending the chronology beyond the limit of radiocarbon, U-series and OSL in the future using paleomagnetic excursions/reversals and tuning against well-dated high latitude paleoclimate records.

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1. Introduction

Although long, continuous records of past climate change from marine sediments are now common, and have provided remarkable insights into past changes in the Earth's climate system over the last few glacial cycles, paleoclimate reconstructions of similar length and continuity from terrestrial environments are less abundant. Therefore, much less is known about the spatial and temporal patterns of past continental climate changes on timescales of tens to hundreds of millennia. However, in recent years, an increasing number of new continental paleoclimate records have been generated from depositional archives like speleothems and lacustrine sediments with sufficient length to compare with marine archives on these timescales. Particularly with the development of flexible drilling platforms designed specifically for lake systems, exceptionally long and continuous lake records have now been obtained from nearly every continent including recent work at: Lake Titicaca (Fritz et al., 2007, 2012; Hanselman et al., 2011), Lake Peten Itza (Correa-Metrio et al., 2012; Mueller et al., 2010), Lake Baikal (Antipin et al., 2001; Kachukov et al., 1998; Prokopenko et al., 2006; Prokopenko and Khursevich, 2010), Lake El'gygytgyn (Brigham-Grette et al., 2007; Glushkova and Smirnov, 2007), Bear Lake (Bright et al., 2006; Jimenez-Moreno et al., 2007), Valles Caldera (Fawcett et al., 2011), Lake Malawi (Johnson et al., 2011; Lyons et al., 2011; Scholz et al., 2011), Lake Qinghai (An et al., 2012) and Lake Bosumtwi (Koeberl et al., 2007b; Shanahan et al., 2012). All of these lake sediment records offer remarkable potential archives of past climate spanning tens of thousands to millions of years.

Developing reliable chronologies for long lacustrine sediment cores can be challenging. Radiocarbon dating is limited to only the past 50 ka, datable ashes are rare in most environments, and other methods such as U-series dating of carbonates and optically stimulated luminescence (OSL) remain relatively unexploited for developing long lacustrine chronologies. The application of oxygen isotope stratigraphy, which is standard practice in the study of marine sediments, is typically not straightforward in lacustrine systems because it requires significant and potentially circular assumptions about the association between lake proxy data variations and orbital forcing.

The difficulties in using these and other approaches to generate reliable, long lacustrine chronologies may hinder the quality of the paleoclimate reconstructions derived from these archives. However, despite the fact that each dating technique is subject to its own uncertainties and potential biases, in combination they are capable of producing robust age models (Colman et al., 2006). The long sediment drill core record from Lake Bosumtwi provides an excellent opportunity to explore these issues as well as to provide insights into strategies for developing age models for both past and future lake drilling operations. In this paper we examine the last ~150 ka of sedimentation, which is best constrained by a set of complementary dating approaches, to assess the most suitable methods for establishing a long sediment chronology; these include: radiocarbon, U-series, optically stimulated luminescence, identification of paleomagnetic excursions and orbital tuning. Dating of the deeper part of the record, which relies primarily on magnetostratigraphy and K–Ar dating of the impact ejecta, is beyond the scope of this paper and will be presented elsewhere.

2. Study area

2.1. Geological setting

Lake Bosumtwi is a small (~10 km diameter) but deep (~75 m) lake filling a 1.07 ± 0.05 Ma meteorite impact crater in the dry tropical forest zone of southern Ghana (06°32′N, 01°25′W (Koeberl et al., 1998). Seismic and sedimentological evidence suggests that this lake has not dried out for at least the last 50–70 ka, and possibly longer (Scholz et al., 2007). The dearth of similar long-lived lake systems from this part of West Africa makes Lake Bosumtwi a unique repository for past climate and environmental information in this region. Furthermore, because of its year-round warmth, its depth and sheltering provided by the surrounding crater walls, Lake Bosumtwi undergoes relatively minimal mixing at depth on seasonal to interannual timescales, and as a result, is anoxic below 15–20 m (Blockley et al., 2008). The maintenance of nearly continuous bottom water anoxia limits bioturbation and allows for the preservation of annual lamina, providing an opportunity for exceptionally high-resolution paleoclimate reconstructions (Shanahan et al., 2008). Lake Bosumtwi is also internally draining and isolated from the regional groundwater system and as a result, is extremely sensitive to changes in the balance between rainfall and evaporation, making it a unique recorder of past climate variations in this region (Shanahan et al., 2007; Turner et al., 1996).

The climate of West Africa is dominated by the West African summer monsoon, which transports southwesterly moisture to the continent from the Gulf of Guinea and the equatorial south Atlantic during the months of May–September. Variations in this system are driven by changes in Atlantic sea surface temperatures, land–ocean temperature gradients and land surface–vegetation feedbacks on timescales ranging from decades to millennia (Kutzbach et al., 1996; Kutzbach and Liu, 1997; Liu et al., 2003; Opoku-Ankomah and Cordery, 1994; Vizy and Cook, 2001; Wagner and Silva, 1994). Exposed paleolake terraces and geochemical, biological and lithologic changes in Lake Bosumtwi indicate that the climate was much drier prior to ~15 ka, became much wetter as the West African monsoon intensified during the early and mid Holocene, and returned to more arid conditions in the late Holocene as the monsoon weakened (Peck et al., 2004; Shanahan et al., 2006; Talbot and Delibrias, 1980). These results are broadly consistent with general circulation model predictions of the monsoon response to changes in northern hemisphere summer insolation over this time period (Kutzbach and Liu, 1997; Liu et al., 2003).

2.2. Fieldwork

During a series of expeditions in 1999, 2000 and 2004, seismic reflection data were acquired from the Bosumtwi crater using high-resolution "CHIRP", multichannel airgun and 1 kHz "boomer" systems, which provided details on sediment stratigraphy and the morphology of the lake subsurface, including a distinctive central uplift associated with the impact structure (Figs. 1 and 2) (Brooks et al., 2005; Scholz et al., 2002). Based on these data, it was estimated that the central uplift of the impact is roughly circular, 1.9 km in diameter and rises ~130 m above an adjacent bedrock depression or "moat" (Scholz et al., 2002). Lacustrine sediment thicknesses in the central crater range from 150 m directly above the uplift to 310 m in the surrounding moat. Lake level lowstands are apparent in both the multichannel seismic and the high-resolution CHIRP data (Brooks et al., 2005; Scholz et al., 2007, 2002; Shanahan et al., 2006), and provide evidence of lake level cycles over the 1 million year history of the lake.

In the summer of 2004, in cooperation with the government of Ghana and the University of Science and Technology in Kumasi, the Intercontinental Drilling Program (ICDP) and the Consortium for Drilling, Observation, and Sampling of the Earth's Continental Crust (DOSECC), we drilled a series of sites along a depth transect in the lake utilizing the GLAD800 coring system (Figs. 1 and 2). Coring