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Lake-level rise in the late Pleistocene and active subaqueous volcanism since the Holocene in Lake Kivu, East African Rift

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ABSTRACT

The history of Lake Kivu is strongly linked to the activity of the Virunga volcanoes. Subaerial and subaqueous volcanoes, in addition to lake-level changes, shape the subaqueous morphologic and structural features in Lake Kivu's Main Basin. Previous studies revealed that volcanic eruptions blocked the former outlet of the lake to the north in the late Pleistocene, leading to a substantial rise in the lake level and subsequently the present-day thermohaline stratification. Additional studies have speculated that volcanic and seismic activities threaten to trigger a catastrophic release of the large amount of gases dissolved in the lake. The current study presents a bathymetric mapping and seismic profiling survey that covers the volcanically active area of the Main Basin at a resolution that is unprecedented for Lake Kivu. New geomorphologic features identified on the lake floor can accurately describe related lake-floor processes for the first time. The late Pleistocene lowstand is observed at 425 m depth, and volcanic cones, tuff rings, and lava flows observed above this level indicate both subaerial and subaqueous volcanic activities during the Holocene. The geomorphologic analysis yields new implications on the geologic processes that have shaped Lake Kivu's basin, and the presence of young volcanic features can be linked to the possibility of a lake overturn.

1. Introduction

Together with Lakes Nyos and Monoun in Cameroon, Lake Kivu is reputed for being one of the three 'exploding lakes' in Africa (Kling et al., 1987; Halbwachs et al., 2004). Lakes Monoun and Nyos erupted in the 1980s resulting in nearly 2000 fatalities. A limnic eruption, commonly referred to as a lake 'explosion', is a result of oversaturation of dissolved gases that accumulate in the stratified depths of the lake. Lake Kivu's large size and population density extend the risk of a limnic eruption to millions of people. The lake's permanently stratified deepwater contains vast quantities of dissolved CO_2; 300 km^3 at STP (standard temperature and pressure), and CH_4; 60 km^3 at STP (Schmid et al., 2005). These gases would erupt from the stratified depths, and consequently mix the lake, if their combined partial pressures were to exceed the hydrostatic pressure of the lake at all depths (Schmid et al., 2005). The CO_2 is a product of magmatism and active volcanism in the lake basin (Degens et al., 1973; Tedesco et al., 2010), whereas the CH_4 is produced by microbial activity in the anoxic sediment (Tietze et al., 1980; Pasche et al., 2011; Bhattarai et al., 2012). Dissolved CO_2 and CH_4 accumulate in the deepwater below the main density gradient centered at 255 m depth. This gradient is sustained by fresh groundwater inputs from above, and salt and CO_2 entering with hydrothermal inputs at greater depths (Schmid et al., 2005).

Volcanic activity has played an important role in the evolution of Lake Kivu, especially that within the Virunga Volcanic Province (VVP) (e.g., Smets et al., 2010b; d'Oreye et al., 2011). The cities of Goma (DRC; the Democratic Republic of the Congo) and Gisenyi (Rwanda), located on the northern shoreline of the lake (Fig. 1), are constructed almost entirely on lava flows. Furthermore, the presence of phreatomagmatic cones along the northern shoreline document the historical occurrences of eruptive events at the lake boundary (Capaccioni et al., 2003). Haberyan and Hecky (1987) estimated that Lake Kivu's northern outflow to Lake Edward was dammed by the lavas of the VVP sometime in the late Pleistocene. This blockage was followed by lake-level rise that eventually drained south along a border fault to Lake Tanganyika at ~10 ka. This fault is occupied by the present-day 'Ruzizi River' (Fig. 1) (Degens et al., 1973).

Several studies have been made on the sediments of Lake Kivu and Lake Tanganyika that date the geological developments contributing

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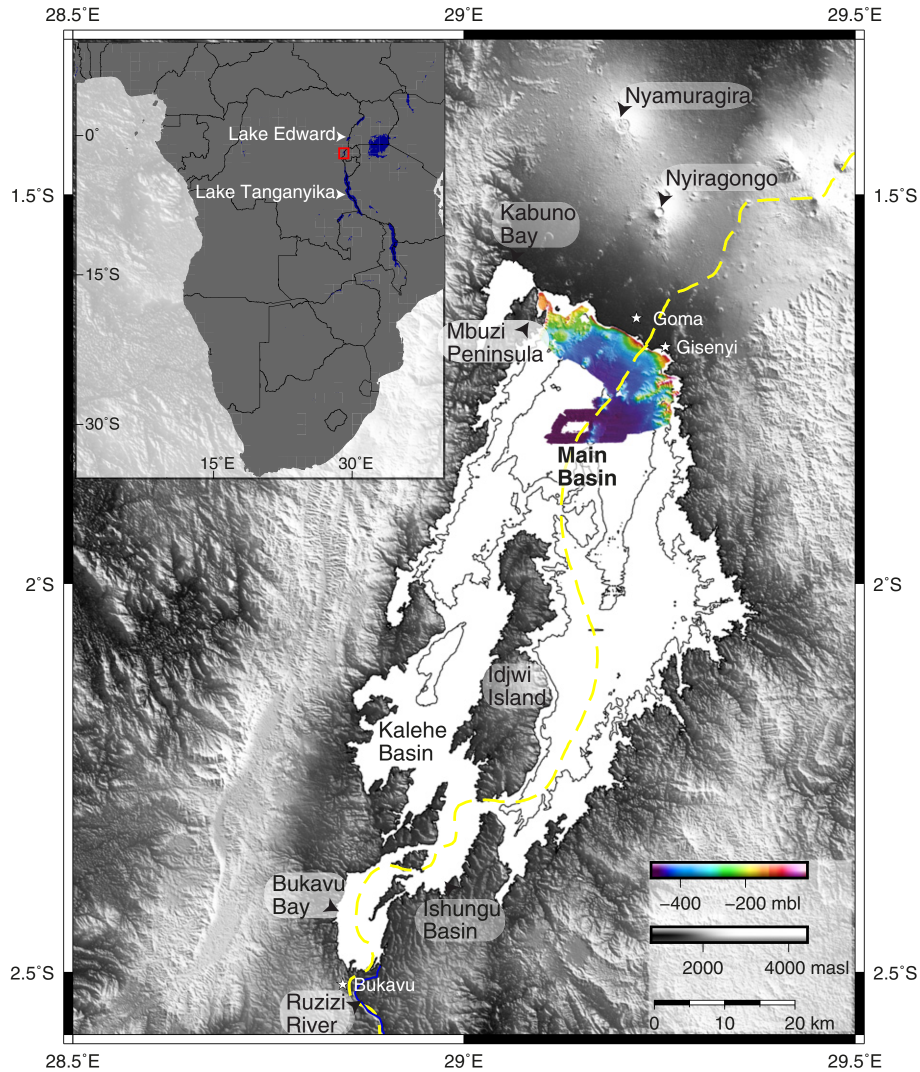

Fig. 1. Overview map of Lake Kivu's basin. The inset represents the location of the Kivu Basin within Africa. Main figure: Gray scale, 30 m ASTER Global DEM (GDEM) data displaying Nyiragongo and Nyamulagira volcanoes north of the lake (ASTER GDEM is a product of METI and NASA). The discontinuous line is the border separating the Democratic Republic of the Congo to the west and Republic of Rwanda to the east. Black contour lines represent the 200 and 400 m depths in the lake. Colored map overlaying the lake illustrates the 224 km^2 area of high-resolution bathymetry data acquired within the Main Basin, and used for analysis of observed features. Lake depths are given in meters below lake (mbl).

to the current state of Lake Kivu. An overview of the proposed events is given from the varying data in the publications, and summarized in Table 1. Core dating on the sediment taken by Degens et al. (1973) in the 1970s was based on radiocarbon measurements of bulk organic carbon, and therefore could be anomalously old due to hydrothermal inputs of CO_2. In summary, Lake Kivu's stratification (state of meromixis) was initiated with its lake-level rise at ~10–14 cal. kyr BP (Table 1). Its alteration from a thermal to a thermohaline stratification was inferred to have been initiated within the last 6 kyr according to Hecky and Degens (1973). The researchers postulated that the change was presented with the onset of hydrothermal spring activity within the stratified depths of the lake (Degens and Kulbicki, 1973). At least two periods are described in literature where there has been a breakdown of the thermohaline stratification linked to intense hydrothermal activity from volcanism within the last 6 kyr (Table 1). Recent acquisition of sediment cores, and radiocarbon dating at subaquatic-tephra layers in Lake Kivu have determined a date of ~0.8 cal. kyr BP for the last lake-overturn event. Ongoing hydrothermal spring inputs into the deepwater of the Main Basin were identified based on data obtained by CTD (conductivity, temperature, and depth) profiling. The lack of knowledge of the lake-floor processes relating to hydrothermal spring activity was the motivation to produce the high-resolution bathymetric map and seismic profiles that are presented here.

The newly constructed map of the Main Basin delineates the geomorphology in Lake Kivu at a resolution that is unprecedented for African rift lakes. Furthermore, our dataset represents the first high-resolution geophysical analysis on the sediment. The Main Basin hosts a variety of geologic structures and processes including: lava flows (e.g., Komorowski, 2003; Halbwachs et al., 2004), faults/fractures (e.g., Peeters, 1957; Degens et al., 1973; Wong and von Herzen, 1974), hydrothermal vents (Degens and Kulbicki, 1973; Schmid et al., 2005; Tassi et al., 2009), earthquake epicenters (e.g., Wong and von Herzen, 1974; Kavotha et al., 2003; Mavonga et al., 2006, 2010; d'Oreye et al., 2011), and dike/magma intrusions (Wauthier et al., 2010, 2012). Volcanic and seismic activities have significantly affected Lake Kivu, but the question concerning the possibility of a lake overturn and expulsion of gas triggered by volcano-tectonic activity remains debated. There is no historical documentation of an event causing a lake overturn, and the last overturn is thought to have occurred at ~0.8 cal. kyr BP (Table 1). Here we discuss new and crucial insights into the development of