Expanded glaciers during a dry and cold Last Glacial Maximum in equatorial East Africa

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ABSTRACT
Glaciers on the world’s highest tropical mountains are among the most sensitive components of the cryosphere, yet the climatic controls that influence their fluctuations are not fully understood. Here we present the first
⁶Be ages of glacial moraines in Africa and use these to assess the climatic conditions that influenced past tropical glacial extents. We applied
⁶Be surface exposure dating to determine the ages of quartz-rich boulders atop moraines in the Rwenzori Mountains (~1°N, 30°E), located on the border of Uganda and the Democratic Republic of Congo. The
⁶Be ages document expanded glaciers ca. 23.4 and 20.1 ka, indicating that glaciers in equatorial East Africa advanced during the global Last Glacial Maximum (ca. 26–19.5 ka). A comparison of these moraine ages with regional paleoclimate records indicates that Rwenzori glaciers expanded contemporaneously with dry and cold conditions. Recession from the moraines occurred after ca. 20.1 ka, similar in timing to a rise in air temperature documented in East African lake records. Our results suggest that, on millennial time scales, past fluctuations of Rwenzori glaciers were strongly influenced by air temperature.

INTRODUCTION
While most middle- and high-latitude glacial extents are influenced by summer air temperatures and, to a lesser extent, winter precipitation (e.g., Oerlemans, 1994; Anderson and Mackintosh, 2006), the mass balance of tropical glaciers is sensitive to changes in air temperature and to a variety of climatic parameters including precipitation, humidity, and cloudiness (Kaser et al., 2004; Mölg et al., 2006; Taylor et al., 2006a, 2006b; Thompson et al., 2009; Hastedrath, 2010). Understanding the climatic controls that influence tropical glaciers is critical to inferring past glacial conditions from past glacial extents (e.g., Mark et al., 2005) and to predicting tropical glacial response to future global warming.

The Rwenzori Mountains, located on the border of Uganda and the Democratic Republic of Congo, host the most extensive glacial and moraine systems in Africa (Kaser and Osmaston, 2002) and provide a unique opportunity to apply surface exposure dating using the cosmogenic nuclide
⁶Be because they are predominantly composed of Precambrian quartz-rich gneiss. At least four prior glacial extents are marked by moraine systems that are in multiple valleys in the Rwenzori Mountains (Osmaston, 1989). We targeted the Lake Mahoma Stage moraines that H. Osmaston mapped and suggested were deposited during the last glacial period (Livingstone, 1962; Osmaston, 1989). At the type locality near Lake Mahoma, a kettle lake in the Mubuku Valley on the eastern side of the mountains, a series of moraines marks former glacial extents down to ~2070 m above sea level (asl) (Fig. 1). At present, Rwenzori glaciers are restricted to elevations above ~4800 m asl, and therefore the Lake Mahoma Stage moraines represent a dramatic glacial response to past climatic conditions.

STUDY SITE AND METHODS
In the Mubuku Valley, the Lake Mahoma Stage moraines include three moraines, which we informally call, from oldest to youngest, the Mahoma-3, Mahoma-2, and Mahoma-1 (Fig. 1). The Mahoma-3 and Mahoma-2 moraines are arcuate terminal moraines at ~3000 m asl that were deposited by a glacier with a catchment area likely located on the eastern side of Mount Baker and Mount Luigi di Savoia that flowed down the Kuruguta and Mubuku Valleys. The Mahoma-2 moraine forms the southeastern margin of Lake Mahoma. The Mahoma-1 moraines are a pair of lateral moraines that extend much farther down the Mubuku Valley to an elevation of ~2070 m asl. Glaciers from Kuruguta, Mubuku, and Bujuku Valleys merged to form the Mahoma-1 extent. The right-lateral Mahoma-1 moraine crosscuts the Mahoma-2 moraine and forms the northwestern margin of Lake Mahoma.

We obtained samples for
⁶Be dating from the right-lateral Mahoma-1 moraine range from 22,930 ± 440 yr ago to 24,040 ± 540 yr ago (⁶Be ages ± 1σ measurement uncertainties) with a mean age of 23,370 ± 470 yr ago (arithmetic mean ± 1σ). Four
⁶Be ages from the right-lateral Mahoma-1 moraine range from 19,240 ± 370 yr ago to 20,520 ± 700 yr ago (⁶Be ages ± 1σ measurement uncertainties) with a mean age of 20,140 ± 610 yr ago (arithmetic mean ± 1σ).

In general, uncertainties in
⁶Be dating arise from production rate and measurement uncertainties as well as geological uncertainties such as boulder surface erosion, cover by glacier ice or vegetation cover or for boulder surface erosion. ⁶Be ages are shown with 1σ measurement uncertainties. We interpret the
⁶Be ages of boulders on the moraines to represent the timing of final moraine construction at the glacial margin. We report
⁶Be ages in years ago (yr ago; i.e., prior to the date of sample collection in A.D. 2012) and thousands of years ago (ka). In contrast, previously published radiocarbon ages described herein and interpretations based on radiocarbon dating are reported as thousands of calibrated yr before present (i.e., prior to A.D. 1950; kyr B.P.).

RESULTS
We measured eight high-precision
⁶Be surface exposure ages of boulders on the Lake Mahoma Stage moraines (Fig. 1; also see Table DR1). Four
⁶Be ages from the Mahoma-2 moraine range from 22,930 ± 440 yr ago to 24,040 ± 540 yr ago (⁶Be ages ± 1σ measurement uncertainties) with a mean age of 23,370 ± 470 yr ago (arithmetic mean ± 1σ). Four
⁶Be ages from the right-lateral Mahoma-1 moraine range from 19,240 ± 370 yr ago to 20,520 ± 700 yr ago (⁶Be ages ± 1σ measurement uncertainties) with a mean age of 20,140 ± 610 yr ago (arithmetic mean ± 1σ).

GSA Data Repository item 2014184, Table DR1 (⁶Be sample data and calculated ⁶Be surface exposure ages), is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.
sediment, snow or vegetation, and postdepositional boulder movement. The \(^{10}\text{Be}\) ages presented here are calculated using a \(^{10}\text{Be}\) production rate determined at a similarly low-latitude, high-altitude location (Kelly et al., 2013) with an estimated uncertainty of \(\pm 6\%\) (cosmognosis.wordpress.com). Measurement uncertainties are \(\pm 3.5\%\) (Table DR1). The \(^{10}\text{Be}\) ages show excellent internal consistency on individual moraines and suggest that the geological uncertainties are small. For example, two boulders from \(<10\ m\) apart on the Mahoma-2 moraine (RZ-2 and RZ-3) yield nearly identical ages of \(22,930 \pm 440\ yr\) ago and \(23,230 \pm 440\ yr\) ago (Figs. 1 and 2). Moreover, the \(^{10}\text{Be}\) ages are consistent with the crosscutting relationship of the moraines showing that the Mahoma-1 moraine is younger than the Mahoma-2 moraine. Our \(^{10}\text{Be}\) moraine chronology is also consistent with a radiocarbon age of organic material in a sediment core from Lake Mahoma (uncalibrated age is \(14,750 \pm 290\ ^{14}\text{C}\) yr B.P.; Livingstone, 1962).

This material (comprising \(\sim 20\ cm\) of organic-rich sediment located \(60\ cm\) above gravelly till at the base of the core) provides a minimum-limiting age on glacial retreat of 17.2–18.6 kyr B.P. (2\(\sigma\) calibrated age range based on IntCal13; Reimer et al., 2013).

**DISCUSSION**

Based on our \(^{10}\text{Be}\) chronology, we suggest that glaciers in the Rwenzori Mountains advanced to near their maximum extent during the last glacial period by ca. \(23.4\ ka\). The next significant moraine set outside of the Lake Mahoma Stage moraines is near the Bigo Bogs, \(~7\ km\) up the Bujuku Valley at \(~3400\ m\) asl, and is estimated to be Holocene in age (Osmaston, 1989; Fig. 1).

The only other locations in Africa where moraines have been dated directly are in Kenya and Tanzania on Mounts Kenya and Kilimanjaro, respectively. Here, the basaltic bedrock types preclude the application of \(^{10}\text{Be}\) dating, and \(^{36}\text{Cl}\) surface exposure dating was applied to determine moraine ages. On Mount Kenya, \(^{36}\text{Cl}\) ages of boulders on presumed Last Glacial Maximum (LGM; i.e., Liki II; Mahaney, 1990) moraines in the Gorges Valley range from \(24 \pm 1\ ka\) to \(32 \pm 2\ ka\), and boulders on Liki II deposits in the Teleki Valley yielded \(^{36}\text{Cl}\) ages of ca. \(19.2–135\ ka\) (Shanahan and Zreda, 2000).
On Kilimanjaro, $^{36}$Cl ages of boulders on the Fourth or Main Glaciation moraines range from 16.4 ± 0.7 ka to 103 ± 5 ka on Mawenzi Peak, from 13.6 ± 0.6 ka to 23 ± 1 ka on the Saddle, and from 12.0 ± 0.4 ka to 28 ± 1 ka on Kibo Peak (Shanahan and Zreda, 2000). Shanahan and Zreda (2000) generally attributed the high variability of the ages to either the influence of nonuniform erosional processes or the presence of $^{36}$Cl inherited from a prior period of exposure. Although rejection of some ages that are clearly outliers yields moraine ages similar to the global LGM (i.e., 20 ± 1 ka for the Main Glaciation moraines on Mawenzi Peak), the scatter in these $^{36}$Cl ages makes comparison with other paleoclimate proxy data difficult. In contrast, the much more tightly defined ranges of our $^{10}$Be ages from the Rwenziro Mountains readily facilitate comparison with other paleoclimate proxy data to assess the climatic conditions that influenced past glacial extents.

To infer the climatic conditions that led to the Rwenziro glacial fluctuations, we compare the Lake Mahoma Stage moraine ages with regional paleoclimate records. Virtually all of the African Great Lakes were nearly or completely desiccated during the LGM (Johnson et al., 1996; Beuning et al., 1997; Gasse, 2000; Russell et al., 2003). Lake Albert, at the northern end of the Rwenziro, was reduced to a shallow, swampy lake surrounded by an arid grassland between ca. 35 and 21.5 kyr B.P., with complete desiccation between 21 and 15 kyr B.P. (Beuning et al., 1997). To the south, lowstand deltas in Lake Edward indicate a 65% reduction in lake volume during the LGM relative to present (McGee et al., 2006). Lakes Albert and Edward both receive substantial runoff from the Rwenziro Mountains and therefore respond at least in part to hydrological changes within the mountains. To the east, aridity is marked by desiccation surfaces in Lake Victoria that suggest a reduction in precipitation of as much as 30% during the LGM relative to present (Johnson et al., 1996). To the west, geochemical data in the Congo Basin suggest an arid LGM (Weijers et al., 1996). To the south, lowstand deltas in Lake Edward indicate a 65% reduction in lake volume during the LGM relative to present (Johnson et al., 2007). While there is limited evidence for relatively moist conditions elsewhere in tropical Africa during the LGM, the records from near the Rwenziro Mountains clearly indicate that the glacial advances to the Mahoma-2 and Mahoma-1 moraines, just prior to ca. 23.4 ka and ca. 20.1 ka, respectively, occurred during regionally dry climatic conditions.

Paleotemperature estimates have been sparse in tropical Africa due to the confounding effects of precipitation on many temperature proxies. New organic geochemical proxies based upon the relative abundances of isoprenoidal and branched glycerol dialkyl glycerol tetraethers [i.e., TEX$_{36}$ (tetrather index of tetraethers with 86 carbon atoms) and MBT-CBT (methylation index of branched tetraethers–cyclization index of branched tetraethers) proxies] have substantially improved our understanding of late Quaternary temperature changes in Africa. Reconstructions from Lake Malawi (Powers et al., 2005), Lake Tanganyika (Tierney et al., 2008), Sacred Lake on Mount Kenya (Loomis et al., 2012), and the Congo Basin (Weijers et al., 2007) indicate that LGM temperatures were 3–5 °C cooler than at present (Fig. 3), compatible with paleotemperature reconstructions from fossil pollen in the Burundi highlands (Bonnefille et al., 1990) that indicate 4 ± 2 °C cooling. In addition, the organic geochemical records from East Africa (i.e., Tanganyika, Malawi, and Sacred Lakes) show the onset of deglacial warming between 21 and 20 kyr B.P., contemporaneous with glacial recession from the Mahoma-1 moraines (Fig. 3). The combined Rwenziro moraine chronology and paleoclimate records thus suggest that the LGM in equatorial Africa was cold enough to drive significant glacial advances despite a decrease in precipitation.

Tropical paleotemperatures are also commonly inferred from past glacial extents using former glacial equilibrium line altitudes (ELAs) and an assumed adiabatic lapse rate. ELAs inferred from Lake Mahoma Stage glaciers in Mubuku Valley are ~3800–4000 m asl and are lower than recent (A.D. 1965) ELAs by ~800–1000 m (Osmaston, 1989; Kaser and Osmaston, 2002; Mark et al., 2005). Present-day ELAs are likely much higher than those determined in A.D. 1965. Assuming an adiabatic lapse rate of ~5.5 °C/km in the Rwenziro Mountains (Eggemont et al., 2010), Lake Mahoma Stage gla-

![Figure 2. Photos of Lake Mahoma Stage moraines and boulders that were sampled and $^{10}$Be dated. A: Right- and left-lateral Lake Mahoma Stage moraines in Mubuku Valley. B: Very large boulder (sample RZ-1) on the right-lateral Lake Mahoma Stage moraine in Mubuku Valley. $^{10}$Be age of the boulder is shown in years ago with 1σ measurement uncertainties. White circle marks standing person for scale. C: Lake Mahoma Stage (Mahoma-2) moraine that bounds Lake Mahoma. D: Two smaller boulders (white arrows; samples RZ-2 and RZ-3) on the Mahoma-2 moraine yield very similar $^{10}$Be ages. See Figure 1 for moraine and sample locations.](image)

![Figure 3. Quantitative paleotemperature reconstructions based on TEX$_{36}$ (see text) from Lake Malawi (dashed line; Powers et al., 2005) and Lake Tanganyika (Tierney et al., 2008) and on branched glycerol dialkyl glycerol tetraethers from Sacred Lake, Kenya (Loomis et al., 2012). Gray bar shows time of deposition of Mahoma-2 and Mahoma-1 moraines, indicating that these were deposited during cold conditions in equatorial Africa. The y-axis value of the moraine ages plotted is arbitrary.](image)
ciers were influenced by temperatures at least 4–6 °C lower than at present. Mark et al. (2005) inferred cooling of ~3–8 °C from ELAs associated with Lake Mahoma Stage glaciers. Due to a drier atmosphere during the LGM, the lapse rate and thus the magnitude of cooling inferred from LGM ELAs may have been larger; however, there are no data independent of the glaciers to quantify past changes in the lapse rate. The highest elevation organic geochemical proxy record from Africa (i.e., from Sacred Lake at ~2400 m asl on Mount Kenya) indicates temperatures ~5 °C lower than at present at the end of the last glacial period (Loomis et al., 2012). Thus, the amplitude of LGM cooling inferred from glacial ELAs is compatible with organic geochemical proxy records.

CONCLUSIONS

10Be surface exposure dating of quartz-rich boulders on glacial moraines in the Rwenzori Mountains yields ages that show excellent internal consistency and are in agreement with a previously published radiocarbon age. Eight 10Be ages of Lake Mahoma Stage moraines indicate deposition during the LGM. These data, combined with dry and cold LGM climatic conditions inferred from regional paleoclimate proxies, strongly suggest a direct correlation between Rwenzori Mountains glacial extents and temperature on millennial time scales. Future research should focus on applying 10Be dating to the mountains of equatorial East Africa: International Journal of Climatology, v. 30, p. 146–152.


Manuscript received 29 December 2013 Revised manuscript received 14 March 2014 Manuscript accepted 19 March 2014

Printed in USA