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Quaternary glaciation in Africa: key chronologies and climatic implications

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ABSTRACT: Multiple episodes of Quaternary glaciation are evidenced on >10 distinct mountain localities throughout Africa, with the best dated sites from Kilimanjaro and Mt Kenya in equatorial East Africa. A general paucity of radiogenic dates constrains the glacial chronology, and regional sequences have largely been based on correlations by relative weathering of features. Excellent glacial moraine preservation and other features of erosion put limits on the spatial extent of palaeoglaciers, and have facilitated advances in palaeo-equilibrium line altitude (ELA) analyses. All radiocarbon dates ($n < 30$) provide minimum ages of deglaciation, and are consistent with a widespread synchronous advance during the Last Glacial Maximum (LGM, 21 ± 2 ka). K–Ar dates on Kilimanjaro lava flows initially recognised up to three glaciations prior to the LGM. Over 100 cosmogenic radionuclide (CRN) ^{36}Cl exposure ages on glacial erratics and bedrock from Kilimanjaro and Mt Kenya date 16 landforms, confirming maximum glacial extent prior to Marine Isotope Stage (MIS) 10. No glacial geological features have been dated to MIS 6. While on Kilimanjaro the CRN ages confirm a clear LGM (MIS 2) maximum, Mt Kenya lacks definitive LGM moraines. Lateglacial advances or stillstands on both mountains are suggested by low-relief moraines dating to 14.6 ± 1.2 ka (two boulders) on Mt Kenya and 16.3 ± 1.9 ka and 15.8 ± 2.5 ka on Kilimanjaro. Multiple moraines upvalley have early Holocene ages ranging from 11.2 ± 0.8 to 8.6 ± 0.2 ka. Isolated and equivocal dates on both mountains also provide speculative evidence that the maximum extent since MIS 5e may have occurred close to 30 ka, similar to sites in South America. New palaeoclimatic understanding from lake and ocean proxies suggests hypotheses for the source of low-latitude climate changes causing the advances that can be tested with improved dates. A high degree of intra-regional variance in ELA is observed, with differences by aspect reflecting precipitation gradients. Future work should include more CRN dates, improved mapping and inverse climate–mass balance modelling. Copyright © 2008 John Wiley & Sons, Ltd.

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KEYWORDS: Africa; glaciation; chronology; palaeoclimate; ELA.

Introduction

African glacial geomorphology is confined to widely dispersed mountain localities and provides an important archive to complement other palaeoclimate proxies and test hypotheses about the timing and geographical nature of Quaternary climatic variations. Continental-scale climate changes in Africa have been tied to global glacial cycles and linked to major evolutionary transitions over the Plio-Pleistocene (deMenocal, 1995). Episodes of mountain glaciation herald entire ecosystem alterations at lower elevations, and understanding the Quaternary climate evolution of Africa was recognised to be important for ecology and evolutionary biology (Livingstone, 1975). Highland regions also play a disproportionately important role in water and ecological resources for Africa, and evidence of changes in these regions over the last 20 ka has instigated research about climatic impacts on human civilisation and natural resources (Messerli and Winiger, 1992). Tracing glacial changes over time in African mountains thus delimits important local-to-regional responses to global-scale climate forcings.

Peculiarities of African geography and geological history enhance the value of the glacier record in understanding Quaternary climate changes, but likewise challenge interpretation. Africa comprises 20% of the Earth's terrestrial surface area and spans almost 35° latitude on either side of the equator, to be the largest tropical landmass on Earth. Africa's discrete highland centres of glaciation are dispersed across a wide span of latitude throughout a diversity of climate regimes (Fig. 1). Given the uncertainties in interpretation of vegetation history

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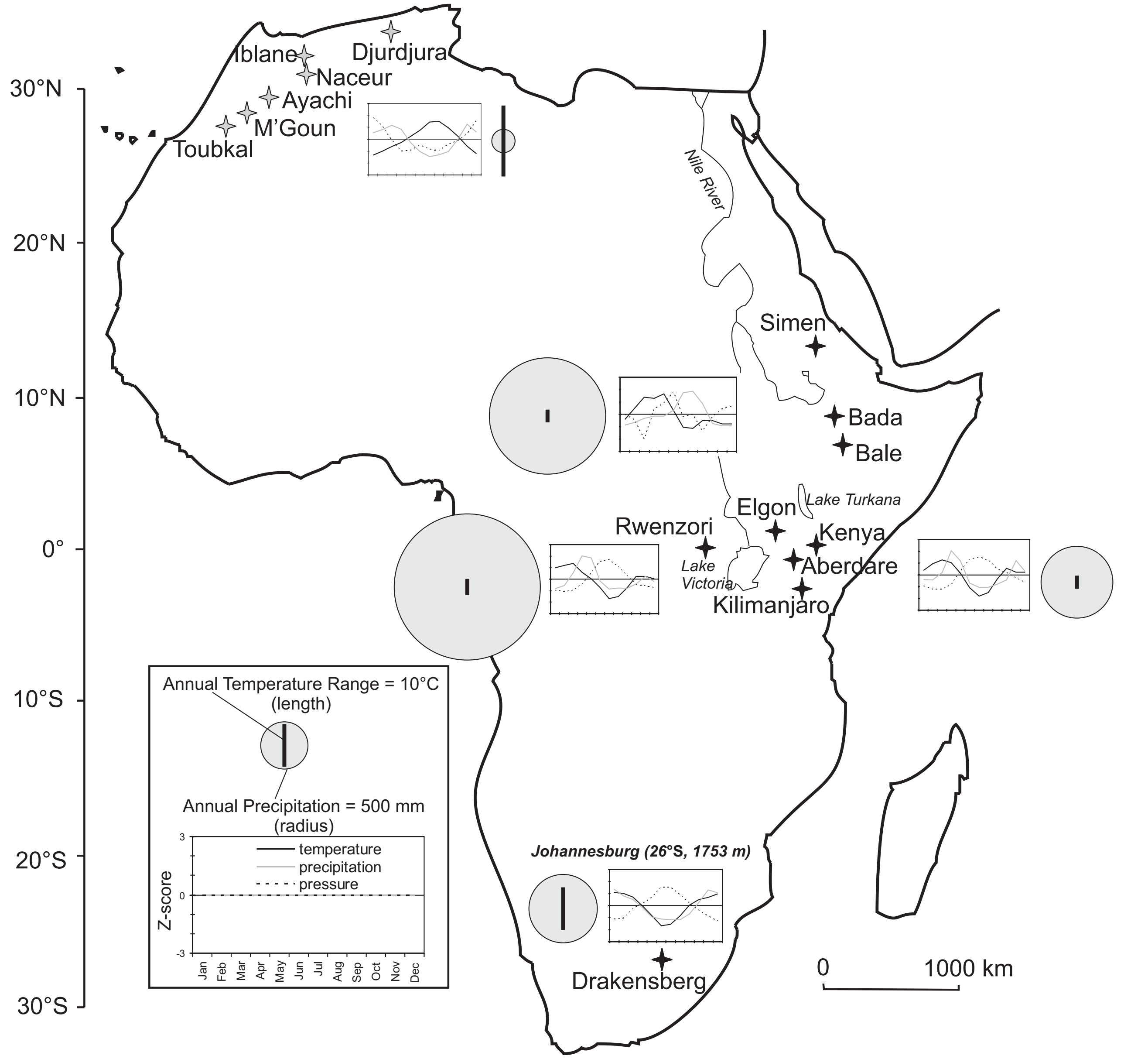

Figure 1 Map of Africa showing mountain localities named in the text. Solid stars have evidence of Quaternary glaciation, with lighter grey shading representing a lack of absolute dates. Also included are climate summaries for representative stations, with scaled symbols tracking magnitude of total precipitation and annual temperature range, as well as monthly variability (*z*-scores) of temperature, precipitation and station-level pressure

related to CO_2 sensitivity over glacial–interglacial timescales (Street-Perrott *et al.*, 1997; Olago, 2001), glacier records provide the only reliable physical proxy of climate at high elevation. However, complexities of Africa's scale and diverse physical geography also challenge the interpretation of the glacial record, since the disparate regions experience very different and highly localised climates. More practically, the glaciated highlands are challenging locations to access, and chronological understanding remains very limited due to a lack of absolute dates. Geomorphological observations of past glaciation in Africa have been documented since 19th-century European explorers, but features remain poorly dated. Relative ages have been assigned to many glacial deposits, and several postglacial and interglacial dates constrain sequences of glaciations, but only one study published to date includes direct radiometric ages of glacier landforms using cosmogenic radionuclide (CRN) dating.

The purpose here is to evaluate the current state of understanding for the timing and nature of Quaternary glaciations, and provide constructive guidance for future work. This paper falls in succession to a number of comprehensive reviews of Quaternary glaciation (Rosqvist, 1990; Kaser and Osmaston, 2002; Osmaston and Harrison, 2005), hydrology (Gasse, 2000), climate dynamics and variability (Nicholson, 1996), vegetation changes (Olago, 2001), late Quaternary climatic change (Livingstone, 1975; Kiage and Liu, 2006), mountain climate and environmental change (Messerli and Winiger, 1992) and equatorial glaciers of East Africa (Hastenrath, 1984; Mahaney, 1989, 1990). To complement and update these previous efforts, this work characterises spatial and temporal dimensions of glacial activity with regard to climate context; it both synthesises the regional patterns and documents chronological and geographical details for palaeoglacier-specific localities. The individual palaeoglacier is thus the basic unit of data tabulated in this review, as prescribed in the recent tropical snowline database project (Mark *et al.*, 2005). Throughout the text, the term *glaciation* will be used to describe a period of glacial advance or stage of moraine

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formation, usually with a site-specific name, while *glacial cycle* refers to a global period of continental glaciation or Marine Isotope Stage (MIS).

The paper begins with an overview of the physical geography of the regions where glacial geological evidence exists and has been documented in previous work. An emphasis on tropical East Africa reflects the importance of this highland region in documenting multiple episodes of Quaternary glaciation. A brief description of relevant glacial geologic methods follows in the third section, including moraine chronology and palaeo-glacier equilibrium line (ELA) reconstruction. The review of Quaternary glacial chronology in the fourth section highlights results from the few best-dated sites in East Africa and summarises them with a time–distance diagram. In the fifth section a discussion evaluates the palaeoclimatic implication of these chronological patterns in relation to other proxies. In conclusion, specific palaeoclimate hypotheses are posed for future tests to be made with refined geomorphological and chronological fieldwork.

Geographical setting

Physiography

The tectonic setting of the African continent imposes a first-order control on both hydrology and glacier formation. Africa lacks continuous mountain chains owing to its passive tectonic margins, and features a broadly elevated plateau form with relatively high mean elevation (~650 m above sea level) compared to other continental blocks. South America is the only other continent to transect the equator with such a large latitude range, but it has a small amount of land at very high elevation and broad areas close to sea level. In contrast, Africa has a large area at intermediate elevation (>1.5 km), no area above 6 km, and very little area close to sea level (Summerfield, 1996). Within this old and elevated continent, evidence of former glaciation occurs on relatively isolated highlands, from the Atlas Mountains bordering the Mediterranean in the north, through elevated plateaus and volcanoes in the East African Rift zone, to the escarpment of South Africa (Fig. 1).

The Atlas Mountains of North Africa (Fig. 2) show evidence of being glaciated, although there are no radiometric dates from the region (Awad, 1963; Hughes *et al.*, 2004). They comprise a series of ranges and plateaus over a 2400 km span from southwestern Morocco through northern Algeria to northern Tunisia that form a major climate divide between the wet Mediterranean northern slopes to the dry southern slopes bordering the Sahara Desert. The mountains are predominantly folded sedimentary rocks formed at the Africa–Eurasia plate boundary, uplifted and deformed during the Mesozoic and Cenozoic. Highest summits of the High Atlas are formed in Palaeozoic granite, rhyolite and andesite, while the rest are predominantly folded sedimentary rocks of Mesozoic carbonate, uplifted in the Jurassic (Hughes *et al.*, 2004). The highest peak, Jebel Toubkal, reaches over 4100 m.

All of the best-dated glacial sequences are found in the East African highlands, where the continent's highest mountains are volcanic cones flanking the two parallel rift systems. With the sole exception of the Rwenzori, mountains only gained sufficient elevation to achieve Pleistocene or recent glaciation by rigorous volcanism that may have obliterated traces of earlier glaciations (Hastenrath, 1984). Kilimanjaro is the highest mountain in Africa, and comprises a composite ridge of three volcanoes, the most recent remaining active throughout the Pleistocene. Kibo is the

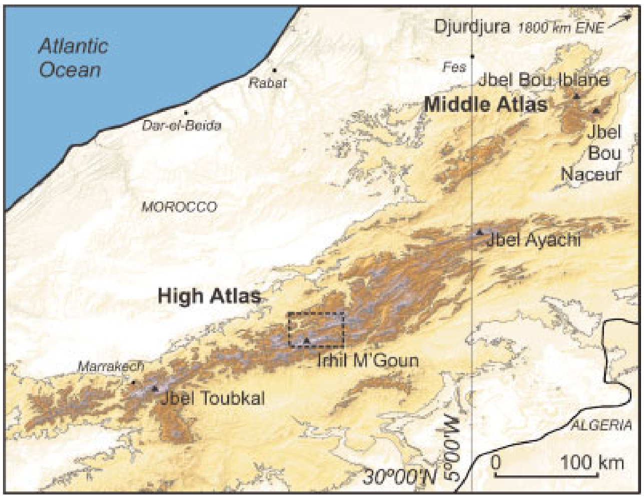

Figure 2 Map of the Atlas Mountains in Morocco, identifying the location of the highest-elevation locations with evidence of glaciation, mentioned in the text and in Fig. 1. The shaded-relief map is generated from shuttle radar topography mission (SRTM) data, with elevation depicted by shaded 1000 m contour intervals; the darkest hues depict terrain over 2000 m. Inset hatched box delimits area of Fig. 13. This figure is available in colour online at www.interscience. wiley.com/ journal/jqs

highest cone (5895 m) and is separated by a wide saddle at 4300–4600 m from Mawenzi (5147 m), a steeply eroded cone 7 km to the east. Principal lithologies on Kilimanjaro include basalt, phonolite, nephelinite and trachyte (Baker *et al.*, 1972). Mount Kenya is a more weathered and dissected cone of a Pliocene shield volcano, with bedrock of basalt, phonolite and trachyte. To the west of the rift, the Rwenzori range is mostly Precambrian rock that has some evidence of Quaternary uplift post-dating glaciation (Whittow, 1966; Osmaston, 1989b). Large, elongated lakes have formed along the downthrusted grabens of the East African Rift Valley, which have provided important palaeoenvironmental archives. This rift system contains three of the world's ten largest lakes, while Africa retains a greater volume of water (~30 000 km^3) in its >670 lakes than any other continent. Many basins in Africa are closed, and large variations in water level over time document regional changes in net hydrological balance.

The Drakensberg Mountains are part of the Great Escarpment and feature summits over 3000 m, including the highest point of South Africa (3482 m). They comprise horizontal sequences of plateau basalts over 1500 m thick, and feature the majority of periglacial and palaeoglacial evidence in South Africa that has been studied and debated over the past half century (Boelhouwers and Meiklejohn, 2002). While previously noted as equivocal (Osmaston and Harrison, 2005), multiple arguments based on geomorphology, sedimentology, topographic analyses and a palaeoclimatic heuristic argue convincingly for small cirque glaciers roughly dated to the Last Glacial Maximum (LGM).

Climate

Symmetrically spanning the equator to cover over 60° latitude, Africa features broadly zonal climate patterns with varying seasonal distribution of precipitation (Fig. 1). The temperature of the continent is generally hot, without large variability and with daily ranges often exceeding annual; about 30% of the continent experiences temperatures in excess of 38°C, and roughly one-third experiences an annual temperature range greater than 6°C. The average annual precipitation over the continent is 725 mm; values range from 1–2 mm in the Libyan Desert to 10 m in Cameroon (Goudie, 1996). The northern and southern limits of the continent are temperate regions displaying Mediterranean-type climate with largely winter cyclonic precipitation from seasonal displacement of the westerlies to lower latitudes, and dry summers. The influence of subtropical anticyclones predominates over arid regions both north and south of the equator, including the Sahara Desert, Earth's largest arid region. Centred on the equator is a central zone of tropical precipitation, where the maximum convection shifts seasonally in response to the maximum insolation. Likewise, a large amount of precipitation occurs in thunderstorms, especially in East Africa.

This generally zonal distribution of temperature and precipitation breaks down over highland regions and under the complicating influence of ocean currents (Goudie, 1996). Certain highland regions in Kenya and Ethiopia receive abundant precipitation throughout the year, supplying runoff to the large East African Rift valley lakes. However, much of the lower-lying terrain (below 1000 m) remains semi-arid, given the rain shadow effects of mountains, the cool upwelling water off the Somali coast and frictionally induced subsidence of the Somali jet paralleling the coast. The complexity of regional mountain climate is also apparent in North Africa, where conditions along the Mediterranean differ drastically from those in the Atlas to the west (Messerli and Winiger, 1992). Cold Atlantic Ocean temperatures also suppress precipitation over the Sahel region.

Tropical East Africa features anomalously low precipitation relative to its latitude. This conspicuous anomaly has been long recognised, and is even more curious for occurring under sustained high elevation near the coast (Trewartha, 1981). It is caused by a number of factors, including wind patterns that typically parallel the coast, the rapid passage of the Intertropical Convergence Zone (ITCZ), and the fact that the converging NE and SE trades lose moisture over the Middle East and Madagascar. Hence East Africa has neither a purely monsoonal nor Mediterranean style climate, but instead has semi-annually occurring rainfall associated with the equatorial rainbelt (de Menocal and Rind, 1996) wherein precipitation patterns are highly localised and complex as a function of topography.

Patterns of rainfall variability seem persistent over time despite different regional controls on mean conditions in Africa. Climate studies reveal that the changes required to induce Pleistocene and Holocene conditions may be of similar magnitude to those occurring occasionally in historical times (Nicholson, 2000). The coherent interannual to decadal variability throughout Africa reflects the influence of aspects of global-scale circulation involving ocean-atmospheric interactions like the El Niño–Southern Oscillation (ENSO). While rainfall in many areas of the continent may be statistically linked to ENSO, it may be more directly a response to sea surface temperature fluctuations in the Indian and Atlantic Oceans occurring in the context of ENSO (Nicholson, 1996; Nicholson and Selato, 2000). There is a general association of wetter continental conditions with colder ocean temperatures, and East Africa shows a particularly strong response to Pacific episodes of ENSO (Nicholson and Kim, 1997).

Modern glacier dynamics

Modern glaciers in Africa are restricted to the summits of the high peaks of Mt Kenya, Kilimanjaro and the Rwenzori. All of these glaciers have undergone dramatic recession since the late 19th century (Kaser and Osmaston, 2002). While ongoing glacier recession is occurring in the context of globally warming temperatures, detailed studies on Kilimanjaro show that the current negative mass balance is actually strongly impacted by regional East African aridity (Kaser *et al.*, 2004) accompanying a dislocation of the upper winds over the Indian ocean (Hastenrath, 2001). Interestingly, the conditions of rapid glacier recession now ubiquitous throughout the global tropics began later on Mt Kenya than the other glacierised regions on the equator, Ecuador and New Guinea (Hastenrath, 2006). On Mt Kenya an abrupt alteration to glacier surface energy balance began only in the 1880s and featured an increased short-wave insolation receipt due to less cloudiness and reduced precipitation, concomitant with sudden drop in water level of large lakes in the region (Hastenrath, 1984). Only during later epochs of observation were these factors overtaken by greenhouse forcing featuring increased temperature and humidity (Hastenrath and Kruss, 1992). The nature of recession on Kilimanjaro also indicates a strong control by aridity and solar insolation (Mölg and Hardy, 2004; Kaser *et al.*, 2004). In the Rwenzori, maps of glacier area loss over time combined with a geographic information system (GIS)-based terrain model of solar insolation demonstrates that the topographic distribution of glacier recession is consistent with increased solar radiation that is interpreted to result from an overall decrease in atmospheric humidity (and clouds) after the late 19th century (Mölg *et al.*, 2003a).

Nonetheless, a related increase in temperature is a related and plausible forcing of ongoing tropical glacier recession in general (Bradley *et al.*, 2006; Thompson *et al.*, 2006) and in tropical East Africa specifically (Taylor *et al.*, 2006a). On a longer time perspective, the summit ice fields on Kilimanjaro are remnants of the Holocene projected to disappear in less than two decades, suggesting that most recently ice is melting more than at any time in at least the last 5 ka (Thompson *et al.*, 2002). The issue of discerning temperature or humidity/radiation as primary climatic forcing of recession remains an issue of considerable debate, as evidenced recently in an exchange over the recent glacial recession in the Rwenzori (Mölg *et al.*, 2006; Taylor *et al.*, 2006a,b). Both increasing air temperature and reduced air humidity are related, and detailed observations of the surface energy budget are needed to quantify relationships between climate parameters and glacier changes.

Previous glacial geological studies

The best-preserved and dated records of Quaternary glaciations in the continent are found in tropical East Africa, including the only published study employing state-of-the-art measurements of *in situ* terrestrial CRN (Shanahan and Zreda, 2000). Here we briefly recount the chronology of discovery and reporting of glaciations. Previous papers have reviewed more thoroughly the history of glacial geological investigations throughout East Africa (Whittow *et al.*, 1963; Hastenrath, 1984; Mahaney, 1989, 1990; Kaser and Osmaston, 2002).

The presently glacierised mountains of East Africa were 'discovered' by European explorations in the 19th century, and soon thereafter published observations documented both present and past extents of ice (e.g. Meyer, 1890). The glacial geology of Mt Kenya was described by Gregory after his 1893 expedition, but he attributed the previously much larger extents of glaciation to formerly higher surface elevation that was subsequently lowered by subsidence and denudation (Gregory, 1894). The first attempt to correlate the glaciations of the region were by Nilsson (1931, 1935), who assumed the glacial advances were coincident with wet pluvial stages discerned from remnant higher lake stands (Nilsson, 1949). While this hypothesis was challenged by others (Flint, 1959), a lack of absolute age control prevented a clear test.

Glacial geological fieldwork after the mid-20th century discovered evidence of multiple glaciations on Kilimanjaro, Mt Kenya and the Rwenzori that were put in a chronological sequence with innovations in radiometric dating. Important fieldwork was completed by the field expeditions of the University of Sheffield to Kilimanjaro (Downie, 1964) and Mahaney to Mt Kenya (Mahaney, 1990). Henry Osmaston also pioneered extensive fieldwork in the region, and developed innovative methods of reconstructing and interpreting palaeo-ELAs (Osmaston, 1989a,b; Kaser and Osmaston, 2002; Osmaston and Harrison, 2005).

Methods

Meaningful climate interpretations from the glacial record require information about both the extent and age of palaeoglaciers. Generally, the highest glaciated East African mountains feature excellent moraine preservation (Fig. 3), with a relative paucity of absolute dates. Multiple glaciations have been identified from distinct deposits (or episodes of erosion) using relative weathering characteristics, stratigraphy or radiometric dates from *in situ* landform material. The volcanic East African Rift setting provided early radiometric dates on till buried by lava flows, even as the same flows eliminated moraine evidence of the full extent of older glaciations (i.e. Downie, 1964). Despite the dearth of dates, African glacial geomorphology has facilitated the reconstruction and spatial analyses of multiple individual palaeoglacier ELAs.

Remnant moraines delimit the extent of palaeoglaciers, from which different methods allow the ELA and change from modern ELA (i.e. snowline depression) to be estimated (Porter, 2001). The palaeoglacier ELA defines the elevation of zero net mass balance, and estimation requires localities with at least identifiable glacier headwall and terminus elevations. With more detailed topographical data and geomorphological constraints on glacier extent, the hypsometric differences between individual palaeoglaciers can be accounted for to more reliably estimate ELA. Osmaston (2005) described these methods and explained how they can be iteratively optimised for multiple individual glacier valleys to validate the vertical mass balance ratio that best accounts for regional palaeoclimate gradients. East African localities are notable because of the statistically significant numbers of individual palaeoglaciers recognised (e.g. $n = 78$ in the Rwenzori). Kaser and Osmaston (2002) discussed the derivation and interpretation of tropical ELAs and explained how tropical glaciers typically feature steeper mass balance gradients than those at higher latitudes, which has been reviewed elsewhere (Mark, 2002). In this review, individual palaeoglaciers are tallied within mountain localities if distinct catchments are discernible with lateral–terminal moraines identified on published maps.

The relatively few radiocarbon dates that have been assigned to glacial events throughout the African continent are all classified as minimum ages, meaning that they derive from organic material emplaced some unknown amount of time after the glacier was present (Bradley, 1999). Any comparisons or unified conclusions about previous glacial events based on minimum ages must therefore be tentative since the disappearance of any glacier depends critically on the site-specific topography in relation to the ice mass (Kaser and Osmaston, 2002). Where radiocarbon dates are published with a range of uncertainty (standard deviation), the ages reported here have all been calibrated using the online version of CALIB 5.0.2 (Stuiver and Reimer, 1993) with relevant calibration data (Reimer *et al.*, 2004).

CRN dating of glacial moraines has been growing in appeal since its techniques were demonstrated to have excellent potential in high-elevation regions where organic material is sparse, or where landscape features exceed the reliability age for radiocarbon. The methods have been described in detail elsewhere (Lal, 1991; Nishizumi *et al.*, 1993; Cerling and Craig, 1994; Zreda and Phillips, 1995; Gosse and Phillips, 2001), to name only a few. In the solitary case where CRN has been applied to African Quaternary glaciation, rock samples were analysed for *in situ* ^{36}Cl concentrations using accelerator mass spectrometry at PRIME Lab, Purdue University. The ^{36}Cl production rate and calculations estimating erosion are needed to make corrections to the apparent age, and most critical at lower latitudes is the geomagnetic corrections. Shanahan and Zreda tested their production rates by dating stromatolites from lakes in the Andes and East Africa with independent radiocarbon dates. Landform ages are developed using a Monte Carlo model to relate the coefficient of variation in raw ages to both soil and boulder erosion rates (Shanahan and Zreda, 2000). This model has not yet been utilised by anyone else, presumably since most studies do not acquire a sufficient number of samples. Without independent erosion rate information, the authors assumed a maximum boulder surface erosion rate of $2\,\text{mm}\,\text{ka}^{-1}$ based on field evidence and results from studies in similar climates.

The quality of dating methodology used to constrain African glacier events in particular regions has been ranked according to a 5-point scale (i.e. Mark *et al.*, 2005). This dating method control (DMC) classifies the chronology of sites such that: DMC = 1 is based on radiometric dating of an identified terminus position; DMC = 2 features geomorphological correlation of terminus position with radiometrically dated feature in the glacier valley; DMC = 3 features correlation with any radiometrically dated feature within a region; DMC = 4 features correlation with a radiometrically dated regional sequence; DMC = 5 is based on a generalised or global glaciation scheme.

The correct climatic interpretation of dated glacial landscape elements like moraines also depends on the location of the dated material relative to the palaeoglacier headwall or highest summit. For example, a date from organic material deposited in a cirque bog close to the summit will more precisely constrain the timing and range of ELA change of a palaeoglacier than a date located near the maximum glacier extension, far below the ELA. Likewise the elevation of both the highest summit and the source of chronological data are provided for each radiometric date in this review.

Finally, site-specific moraine maps have been generated using digital elevation data from the shuttle radar topography mission (SRTM). Hole-filled seamless SRTM data V1, 2004, were acquired in ARC GRID format, WGS84 datum, from the International Centre for Tropical Agriculture at: http://gisweb.ciat.cgiar.org/sig/90m_data_tropics.htm. The SRTM data were viewed and processed in ArcGIS, using the Grid and Surface commands in the Spatial Analyst extension. Colouring was achieved with 200 m graded classification, applying a hillshading with *z* factor of 0.2. The SRTM grids covering all sites in East Africa and Ethiopia were joined to one mosaic grid with identical base contour (600 m) and total relief to yield consistent shading between regional maps. The Atlas Mountains were shaded with the same graded colour ramp starting from a base contour at sea level.

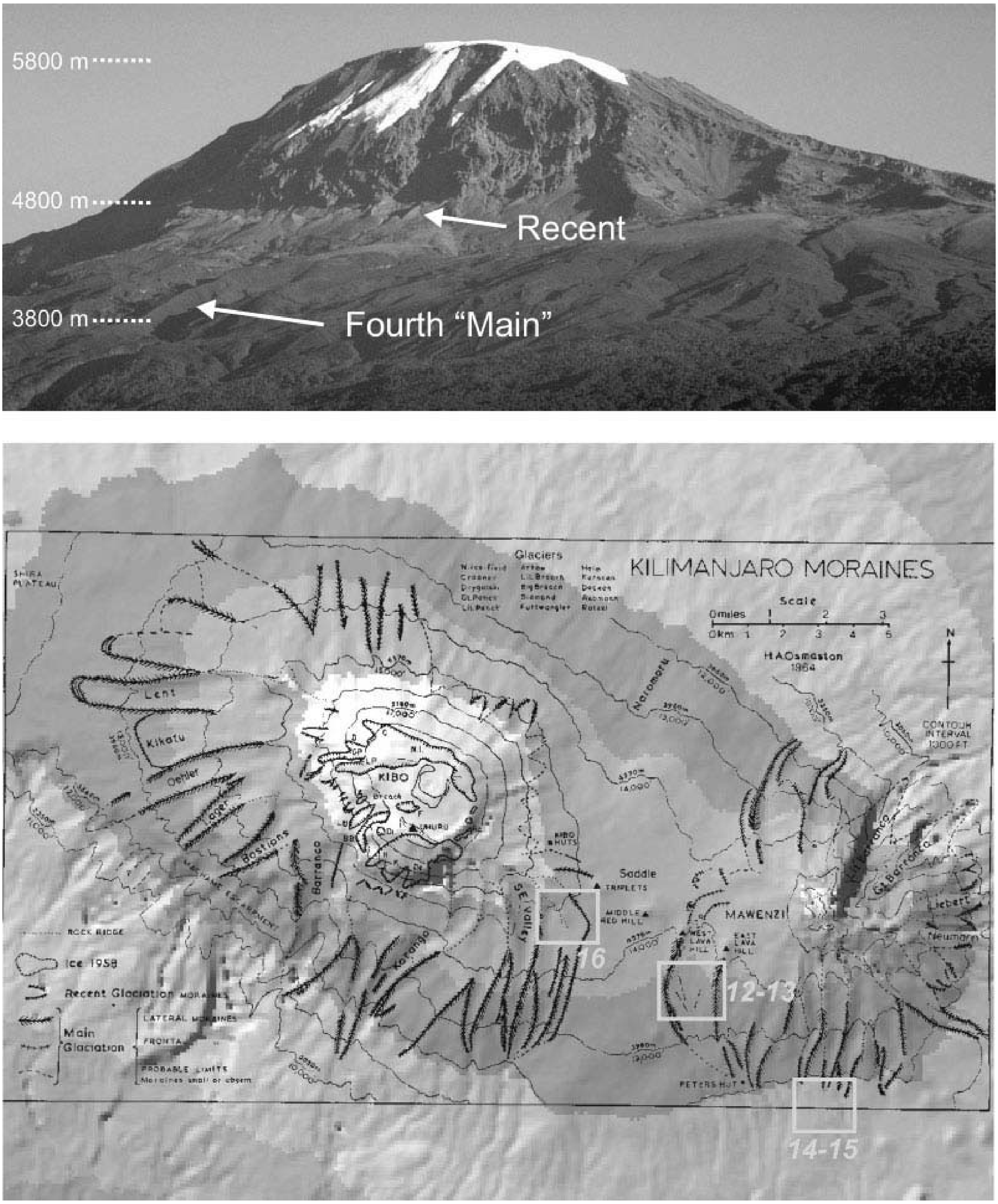

Figure 3 Top: Oblique photo of southern side of Kibo from Moshi (~1000 m) taken January 2006. Moraine ridges clearly seen in shadows are named according to Downie's (1964) classification. Bottom: Shaded digital elevation model (DEM) of Kilimanjaro, with a sketch map (Osmaston, 1965) showing moraines of the Main and Little glaciations overlain to highlight the relief and identify individual named palaeoglacier valley troughs. Boxes surround sites of CRN ages of Shanahan and Zreda (2000), numbered according to Table 3

Chronological data and palaeoglacier extent

In all of Africa there are nine localities with evidence of former glaciation that have absolute age control based on radiometric dates (Table 1). The best-dated locations are in East Africa, where 122 *in situ* cosmogenic ^{36}Cl ages from moraine erratics sampled on Mt Kenya and Kilimanjaro support a chronostratigraphic framework (Shanahan and Zreda, 2000). This impressive dataset has rarely been duplicated in scale for glacial geological studies, even if the dates remain problematic given uncertainties in production rates (Zreda and Swanson, pers. comm.). Here we review aspects of the glacial evidence at each locality, including the nature of the geomorphological evidence, specific context of radiometric dates and the

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spatial dimensions of the palaeoglaciers. We focus primarily on key East African regions, but also include brief discussions of other regions where chronological data and/or moraine evidence for Quaternary glaciations exist. Specific radiocarbon and CRN samples are tabulated in detail (Tables 2 and 3, respectively).

Kilimanjaro

Multiple moraine stages are clearly evidenced on Africa's highest peak (Fig. 3). The glacial sequence was elucidated during explorations from the late 19th to mid 20th century (Osmaston, 1989a; Rosqvist, 1990). During the earliest ascents of Kilimanjaro by Europeans, large moraines and striae far beyond modern glacier termini, and glaciofluvial sediments were recognised buried by lava flows (Meyer, 1890). Two expeditions by the University of Sheffield in the 1950s featured careful exploration that amplified the early moraine maps and refined a chronology of named glaciations (Table 4). Ages obtained on lava flows enabled identification of six separate glaciations before the modern receding ice extent, although aerial extent was not able to be established before the fourth advance (Downie, 1964). Deposits from the first two advances bounded by lava flows were K–Ar dated to 500 ka and 300 ka BP (Humphries, 1972). The Third episode was assumed to be 150–125 ka by relative age considerations and also assumed to be most spatially extensive based on boulder beds at 4000 m and striae at 3000 m, even though no terminal moraines are preserved. Osmaston (1989b) contested this point, suggesting that a lack of evidence made the event unreliable.

The Fourth glacial episode was also named the Main stage, as its evidence in well-formed moraines and cirques is best preserved. This advance was presumed to be LGM, and features the most continuously well-preserved moraines terminating at 3400 m. The Little and Recent glaciations were considered post-Pleistocene, though without dates. The Little Glaciation was considered indistinguishable from the Main stage by Osmaston (1989b), and thus not considered a separate event, while Hastenrath (1984) considered the Main Glaciation to have comprised two events. Interbedded lavas and glacial deposits are notably absent on the Shira and Mawenzi cones, implying that volcanic activity on these peaks ceased before glaciation. Moreover, Downie (1964) explained that much better-formed Pleistocene cirques are found on Mawenzi and not Kibo because lavas filled the cirques on Kibo, while repeated glacial events over time sculpted cirques on Mawenzi.

Shanahan and Zreda (2000) sampled the tops of 'large boulders' on moraine crests from the southern slopes of Mawenzi and the Saddle between Kibo and Mawenzi. They focused sampling on moraines ascribed to the Fourth (Main) and Little Glaciations. However, they also sampled boulders from in front of the Main Glaciation moraines, termed the 'oldest' moraines and likely belonging to either Second or Third Glaciation stage, and from bedrock and boulders at the previously estimated limit of the Third Glaciation.

Based on the CRN results (Table 3), the Fourth or Main Glaciation on Kilimanjaro is the LGM, reaching maximum extension at 17–20 ka BP. However, the Little Glaciation is statistically indistinguishable from the Fourth Glaciation moraines sampled SW of Mawenzi, given the large spread in ages (16.3 ± 1.9 ka and 15.8 ± 2.5 ka, respectively). The 'oldest' moraines yielded ages that ranged from 74 to 355 ka (0.49 coefficient of variation), but were assigned a tentative age of 360 ka based on the maximum age. The bedrock sample provided an infinite age of >660 ka, interpreted to be caused by previous exposure. Regardless, the results confirm that at least one glaciation on Kilimanjaro pre-dates the last glacial cycle (Fig. 4).

Palaeoglaciers on Kilimanjaro had the form of radiating tongues from a central ice cap on the volcanic summits of Kibo and Mawenzi. This complicates the reconstruction of individual palaeoglacier dimensions, particularly the headwall and accumulation area, which limits the methods of palaeo-ELA estimation. Osmaston (pers. comm., 2003) aggregated the LGM ELA estimates into aspect classes (Osmaston and Harrison, 2005). The lowest ELA was 3930 m on the E side of Mawenzi, and the highest was 5180 m for the NE side of Kibo. Mapping individual palaeoglacier extensions in aspect class clarifies the spatial nature of this gradient (Fig. 5). This reflects a gradient with heavier precipitation on the E side, as in the modern situation, and suggests a possible rain shadow effect for Kibo downwind of Mawenzi.

Mount Kenya

Mount Kenya (Fig. 6) is located on the Equator, and features the richest record of scientific observations of all tropical glaciers extending back to the 19th century and including a decades-

Table 1 Summary information for African mountain localities

Mt/Locality	Country	Long.	Lat.	Summit elevation (m)	DMC	Palaeoglaciers	Radiometric dates	Evident glaciations
Atlas	Morocco, Algeria	–3.8	33.5	4165	5	7 ?	0	3
Simen	Ethiopia	38.5	13.3	4543	2	20	5	2
Bada	Ethiopia	39.4	7.9	4210	2	18	1	2 ?
Bale	Ethiopia	39.9	6.9	4370	2	2	3	2
Elgon	Uganda, Kenya	34.5	1.1	4320	2	2	2	1 ?
Rwenzori	Uganda, Congo	29.9	0.4	5109	2	78	1	5
Ithanguni (Kenya)	Kenya	37.5	−0.1	3894	3	7	0	3 ?
Batian (Kenya)	Kenya	37.3	−0.2	5199	1	12	82	6 ?
Aberdare	Kenya	36.6	−0.3	4002	2	9	1	1
Kibo (Kilimanjaro)	Tanzania	37.3	−3.1	5894	1	10	12	6 ?
Mawenzi (Kilimanjaro)	Tanzania	37.5	−3.1	5147	1	13	31	6 ?
Drakensberg	South Africa	29.29	−29.56	3275	1	2	3	1

'DMC' refers to the dating method control (explained in the text); 'Palaeoglaciers' lists number of discernible individual glaciers based on topographic maps and moraines; 'Radiometric dates' is the number of absolute ages from region; 'Evident glaciations' refers to number of advances established by published field observations, with question marks for uncertainty.

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Table 2 Radiocarbon dates. Numbered list of radiocarbon dates recovered in African mountain localities. Each date is keyed to a unique identifying number (No.) and contains geographic information, laboratory identifier (Lab ID, where available from literature) and calibrated age based on CALIB 5.0.2 (Stuiver and Reimer, 1993; Reimer *et al.*, 2004). Additional sample description, commentary and references are provided for each date, as well as interpreted geomorphological significance (Min. = minimum, Max. = maximum age)

No.	Mt locality	Site location	Lat.	Long.	Elevation (m)	Summit (m)	^{14}C a BP	95.4% (2σ) cal. age ranges (BP)	Feature dated	Lab ID
1	Simen	Analu 12, Mesarerya 1, or Bwahit 1 valley	13.25	38.2	4175	4430	4 120 ± 90	4 428–4 839	Moor	B-3043
2	Bada	Mt Bada, glacier 13, Bog 3	7.88	39.4	4133	4180	11 500 ± 200	13 020–13 764	Bog	
3	Bale	Tamsaa swamp on N side of Bale Mts	7.17	39.83	3000	4370	13 180 ± 250	14 939–16 399	Swamp	LGO 283
4	Bale	Garba Goracha lake, Togona Valley	6.91	39.91	3950	4370	13 950[a]		Lake	
5	Bale	Near E edge of plateau N of Badegesa Hill	6.85	39.77	4000	4370		15 600 ± 255	Swamp	
6	Elgon	Lake Kilimili, S slopes of Mt Elgon	1.1	34.57	4150	4302	11 012 ± 135	12 808–13 188	Lake	SRR-1118
7	Elgon	Lake Kilimili, S slopes of Mt Elgon	1.1	34.57	4150	4302	10 708 ± 230	11 973–13 112	Lake	SRR-1120
8	Ruwenzori	Mubuku valley, R-lat. from Kuruguta trib valley	0.35	29.97	3000	5109	14 700 ± 290	16 860–18 649	Lake	I-556
9	Aberdare	Bog near summit of Mt Satima	0.32	36.6	3800	4001	12 200		Bog	
10	Kenya	Naro Moro Tarn	−0.17	37.3	4188	5199	6 070 ± 210	6 480–7 341	Lake	St-9072
11	Kenya	Naro Moro Tarn	−0.17	37.3	4188	5199	4 135 ± 70	4 515–4 839	Lake	St-9205
12	Kenya	Hobley Valley	−0.18	37.33	4205	5199	5 265 ± 170	5 656–6 324	Lake	St-10681
13	Drakensberg	Tsatsa-La-Mangaung ridge, trench 1	−29.56	29.29	3080	3275	13 790 ± 110	16 003–16 880	Moraine	Gr-A 21456
14	Drakensberg	Tsatsa-La-Mangaung ridge, trench 2	−29.56	29.29	3040	3275	17 300 ± 100	20 133–20 791	Moraine	Gr-A 21459
15	Drakensberg	Tsatsa-La-Mangaung ridge, trench 3	−29.56	29.29	3020	3275	11 700 ± 100	13 390–13 727	Moraine	Gr-A 21457

No.	Sample description	Interpreted significance
1	Moor deposits on ground moraine	Min. age of deglaciation from presumed LGM
2	Organics near base of core ('Bog 3')	Min. age of deglaciation
3	Bulk organic matter from 140–150 cm in 1.8 m core	Min. age of deglaciation of Bale mountains
4	Organics near base of 16 m core	Min. age of deglaciation
5	Organics near base of 2.6 m core	Limits the extent of LGM ice on east of plateau
6	Basal lacustrine organics	Min. age of deglaciation
7	Basal lacustrine organic	Min. age of deglaciation
8	Organics above glacial silts in 6 m lake core	Min. age of kettle lake formed in deglaciation
9	Organic peat near base of core in cirque	Min. age of deglaciation
10	Core of lake located just below terminal moraine	Max. age of glacial advance and moraine formation because below seds id'd as till
11	Core of lake located just below terminal moraine	Min. age of moraine and ice advance, as it is at contact of organic rich gyttja over till
12	Core of lake behind moraine at similar elevation to Naro Moro Tarn	Min. age of moraine and presumed ice advance
13	Trench in ridge, soil organic matter (SOM) at 1.5 m depth	Min. age of moraine and presumed ice advance
14	Trench in ridge, SOM at 1.35 m depth	Min. age of moraine and presumed ice advance
15	Trench in ridge, SOM at 1.45 m depth	Min. age of moraine and presumed ice advance

No.	Comments	Reference
1	Assumed to be Bwahit valley moor, since text is not specific; author interprets 7°C cooler, drier	Hurni (1989)
2		Osmaston and Harrison (2005); Hamilton (1982)
3	Site is well outside the moraine limit. Value is in pollen indicating a cold climate	Mohammed and Bonnefille (1998)
4	Core still being analysed by M. Umer	M. Umer (pers. comm, 2002)
5	Only age estimate outside limit of the Big Boulder Moraine (BBM); calendar BP age as reported	Zech (pers. comm.); Osmaston and Harrison (2005)
6	Could be reoccupation of cirque	Hamilton and Perrott (1978)
7		Hamilton and Perrott (1978); Rosqvist (1990)
8	Base of core was 60 cm deeper with est. age 16 000 and terminus of glacier reached 800 m lower	Livingstone (1962); Kaser and Osmaston (2002)
9	Moraines and glaciation limits are not reliably known (Hastenrath, 1984)	Perrott (1982); Osmaston and Harrison (2005)
10	Changes Mahaney's interpretation of 12 ka Neoglacial; questionable source of date; no independent evidence	Mahaney (1987); Holmgren (1987)
11	Again, not clear what material is dated	Johansson and Holmgren (1985)
12	Used to substantiate mid-Holocene Neoglacial advance; similar to Holmgren at Naro Moro Tarn	Perrott (1982), cited in Mahaney (1987); Holmgren (1987)
13	Not clear how 3 ages relate stratigraphically; assumed to all date 1 or 2 LGM–Lateglacial advances	Mills and Grab (2005)
14	Not clear how 3 ages relate stratigraphically; assumed to all date 1 or 2 LGM–Lateglacial advances	Mills and Grab (2005)
15	Not clear how 3 ages relate stratigraphically; assumed to all date 1 or 2 LGM–Lateglacial advances	Mills and Grab (2005)

[a] Age uncertainties unavailable, so no calibrated age range possible.

Table 3 CRN ages. Numbered list of cosmogenic radionuclide ^{36}Cl exposure ages of landforms on Kilimanjaro and Mt Kenya, from Shanahan and Zreda (2000). Each numbered (No.) landform age relates to a range of samples, identified by a sample ID. Sample description, interpreted significance and comments fields include further information on the published landform age

No.	Mt locality	Site location	Moraine stage	Lat.	Long.	Elevation (m)	Summit (m)	Landform age (cal. a BP)	# ages	Sample ID (range)
1	Kenya	Teleki Valley	Teleki	−0.17	37.28	3050	5199	255–285k	6	GV97-(17–23)
2	Kenya	Teleki Valley	Liki II	−0.22	37.25	3794	5199	64 000 ± 40 000	10	TV97-(7–16)
3	Kenya	Teleki valley	Liki III	0.23	37.38	4150	5199	10 200 ± 500	7	TV97-(45–51)
4	Kenya	Teleki valley	Liki IIIA	0.23	37.38	4150	5199	8 600 ± 200	7	TV97-(52–58)
5	Kenya	Point Lenana	(Deglaciation)	0.2	37.39	4985	4985	4 100 ± 200	1	PL97-68
6	Kenya	Gorges valley	Liki II	−0.23	37.45	3500	5199	28 000 ± 3 000	6	GV97-(33–38)
7	Kenya	Gorges valley	Liki IIA	−0.23	37.45	3470	5199	14 600 ± 1 200	2	GV97-(39–40)
8	Kenya	Gorges Valley	Liki I	−0.23	37.45	3500	5199	355–420k	3	GV97-(30–32)
9	Kenya	Gorges Valley	Naro Moru	−0.20	37.45	3740	5199	55 000 ± 23 000	8	GV97-(74–81)
10	Kenya	Gorges valley	Liki III	0.21	37.35	4369	5199	14 100 ± 600	5	GV97-(69–73)
11	Kenya	Gorges valley	Gorges	0.17	37.5	2956	5199	6 600 ± 900	3	GV97-(26–29)
12	Kilimanjaro	Mawenzi, Lavahugel Valley	Fourth (Main)	−3.17	37.43	4100	5147	17 300 ± 2 900	7	MP97-(94–100)
13	Kilimanjaro	Mawenzi, Lavahugel Valley	Little and Fourth	−3.17	37.45	4194	5147	15 800 ± 2 500	12	MP97-(101–113)
14	Kilimanjaro	Mawenzi, 3rd Sud Tal valley	Fourth (Main)	−3.19	37.54	3500	5147	20 000 ± 700	3	MP97-(87–92)
15	Kilimanjaro	Mawenzi, 3rd Sud Tal valley	Third (Oldest)	−3.21	37.47	3450	5147	>360 000	5	MP97-(81–86)
16	Kilimanjaro	Kibo, East of SE Valley	Fourth (Main)	−3.15	37.48	4600	5894	13 800 ± 2 300	4	KB97-(119–122)

No.	Sample description	Interpreted significance
1	Well-rounded boulders (up to 2.0 m) on broad, gently sloping moraine	MIS 8 stage but 500 m lower than older Liki I on E slopes
2	No clear moraine; well-rounded, heavily weathered boulders (up to 2.0 m)	Non-uniform erosion by meltwater (?) or prior exposure
3	Fresh boulders (up to 1.0 m), no evident erosion, closely spaced moraines	Closely constrains the age of Liki III advance
4	Fresh boulders (up to 1.0 m), no evident erosion, closely spaced moraines	Wide range suggests a composite formation of Liki III and later advance at 8.6 ka
5	Striated and polished bedrock on summit	Minimum deglaciation age
6	Fresh boulders (0.5–1.0 m) on crest of well-defined moraine just inside Liki I	Dates the Liki I directly as slightly older than global LGM
7	Boulders with well-preserved, low-relief moraines inside large Liki II ridge	Minimum date for Liki II deglaciation
8	Very large boulders (2.0–3.0 m) on well-defined, steep-sloped moraine	Puts Liki I far older than previous estimates
9	boulders (1.0–2.0 m) from isolated till deposit on ridge top interfluve	Uncertain deposit origin
10	3 boulders, 2 bedrock samples not shown on map	Age is indistinguishable from IIA
11	The only four boulders visible on crest; small (<0.5 m), relatively fresh	Young ages, sharp relief, stratigraphy suggest non-glacial origin
12	Boulders from R. lateral moraine SW Mawenzi	Juxtaposition of landforms from Little and Fourth glaciations
13	Boulders from well-preserved recessional moraines	Juxtaposition of landforms from Little and Fourth glaciations
14	Boulders (up to 3.0 m) on well-defined moraines (up to 30 m)	Clear LGM age for Main glaciation; this landform age excludes 3 samples
15	Intensely weathered boulders (0.5–3.0 m) beyond Fourth Glaciation limit	Oldest advance discernible by moraines; may be First or Second stage
16	Unweathered boulders (1.0–2.0 m) on both moraine loops and striated bedrock	Imply moraines are recessional from Main glaciation

No.	Comments
1	Erosion model used to get age; one outlier 531 ka was removed
2	High variance cannot be modelled
3	One sample not included; age within range of calibrated ^{14}C min. ages from lakes (8.5–15 ka)
4	With one exception (5.9 ka), all samples fall in two groups: 11.2 ± 0.8 ka; 8.6 ± 0.2 ka
5	Typo in data sheet says elevation is 5200 m
6	Similar age to 30 ka palaeosols in Teleki valley; correlative Teleki moraine has variable age: 19–135 ka
7	Used to compute rate of retreat (3 m a^{-1}) in combination with erratics (13.0 ± 0.2Yka) 5 km up valley
8	Erosion model used to get age
9	Palaeomagnetics on originally dated to >730 ka; young age, large variance and location are problematic
10	These ages are not discussed in text and do not appear in location map
11	Soil pit (2.5 m) revealed well-sorted fine sand, silt and no gravel, cobble, or boulder; little soil
12	Large spread on age; text describes L-lateral, but map shows R-lateral; table age here not same as text
13	Statistically indistinguishable ages between Little and Fourth
14	6 boulders sampled, but 3 outliers eliminated to reduce variance
15	Excludes bedrock date of 663 ka; the 5 ages range 74–355 ka
16	Boulders more reliable; 3 bedrock samples disregarded as too old (23.0 ± 5 ka) assuming prior exposure

long glaciological monitoring programme on the largest glacier, the Lewis Glacier (Hastenrath, 2006). The highest summit, Batian (5199 m), is a central plug that has been deeply scoured by glaciers, and a secondary volcanic cone on the eastern flank, Ithanguni (3894 m), also was formerly glaciated. Deep valleys radiating from the central plug evidence much larger glaciers in the past, while only small remnants of glaciers persist presently.

Table 4 Kilimanjaro glaciations. Key to named glaciations discussed in text, with absolute ages based on potassium–argon (K–Ar) and relative weathering (Rel.), and cosmogenic nuclide ^{36}Cl exposure (CRN). Locale refers to Kibo (K), Mawenzi (M) or the Saddle (S) between peaks. Minimum elevation in metres derived from literature. References are abbreviations of authors: D, Downie (1964); S&Z, Shanahan and Zreda (2000)

Glaciation	Age	Type	Description	Locale	Min. elev. (m)	Ref.
First	500 ka	K–Ar	Boulder bed over trachy basalt, below phonolites	K	4100	D
Second	>360–240 ka	K–Ar	'Romb porphyry' eroded, overlain by moraines	K	?	D
Third	150–120 ka	Rel.	Boulder weathering; presumed striae at 3000 m	K,M	< 3200	D
	>360 ka	CRN	Max. of boulder age; uncertain glaciation	M	3450	S&Z
Fourth (Main)	17–20 ka	CRN	Very clear moraines on Kibo and Mawenzi	M,S	2500	D, S&Z
Little	14–16 ka	CRN	Not statistically distinct; recessional from Main	S	4200	S&Z

Observations dating to the 19th-century expeditions of Gregory (1894) recorded evidence of past glaciations on Mt Kenya. Moraine maps constructed by Nilsson (1931, 1949) were consistent with the earlier observations. Subsequent field observations distinguished two glaciations, and Older and Younger, as well as a minor recent glacial advance (Baker, 1967). The evidence for the Older glaciation is fragmentary, but the Younger comprises a sequence of glaciations distinguished by moraine morphology. Hastenrath (1984) provided an independent map of the complete glaciated area, and correlated the four stages of the Younger Maxima glaciation with the Fourth or Main Glaciation on Kilimanjaro.

Mahaney (1989, 1990, 2004) used relative dating evidence (soil development, loess thickness, rock weathering and vegetation coverage) to suggest that two glaciations, named pre-Teleki and Teleki, occurred before 100 ka. Palaeomagnetic data suggested that pre-Teleki till was emplaced in the upper Matayuma magnetic epoch before 740 ka BP. Mahaney subsequently identified two pre-Teleki tills in an end moraine close to the glacial limit, and a third pre-Teleki till. The older till distribution is not well known, but its location on interfluves suggests deposition by an ice sheet extending down to ~2850 m (Rosqvist, 1990; Mahaney *et al.*, 1991). The Teleki tills are identified on valley floors and are associated with better-preserved moraines. The deposits are found just below 3000 m in some basins, and feature large erratics of syenite and phonolite (Mahaney, 1979). The deposits have been dated with thermoluminescence to be at least 100 ka BP (Charsley, 1989). In total, Mahaney has identified five Pleistocene glaciations and two Neoglacial advances on Mt Kenya (Mahaney *et al.*, 1991; Mahaney, 2004). The Pleistocene advances are (oldest to youngest): Gorges, Lake Ellis, Naro Moru, Teleki (considered MIS 6) and Liki (last glaciation) (Table 5). While little is known of the initiation of Liki, Mahaney claims Liki II and III are substages dated at pre 25 ka and post 12.5 ka, respectively. The Neoglacial advances are the Tyndall and Lewis, identified as ~1000 and ~100 a BP, respectively, based on lichenometry and historical records.

Shanahan and Zreda (2000) revisited Mt Kenya and used *in situ* cosmogenic ^{36}Cl samples from erratics to date moraines in the upper and lower Teleki valley and Gorges valley, on the east and west sides of the central Batian peak (boxes on Fig. 6).

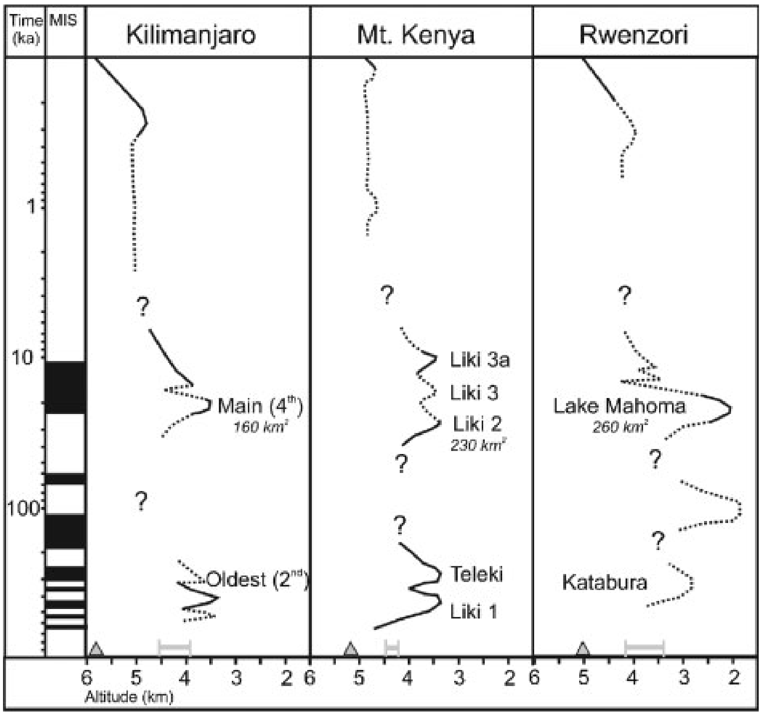

Figure 4 Time–distance diagram for the three most comprehensively mapped and/or dated glaciated mountain localities of East Africa: Kilimanjaro, Mt Kenya and Rwenzori. Time is log-scale, showing alternating black–white tones to demarcate Marine Isotope Stage (MIS), with even-numbered stages in black. Distance represents elevation range, and lines reach to lowest elevation of moraines (km above sea level) of respective glacial advance. Triangles indicate highest summit elevation, and the grey range bar shows the best estimate of LGM ELA. Solid lines indicate good age control and moraine extent; dashed lines indicate good moraine preservation but lack of absolute dates; question marks are unknown given discontinuous stratigraphy. Estimated total ice area (km^2) is provided in italics

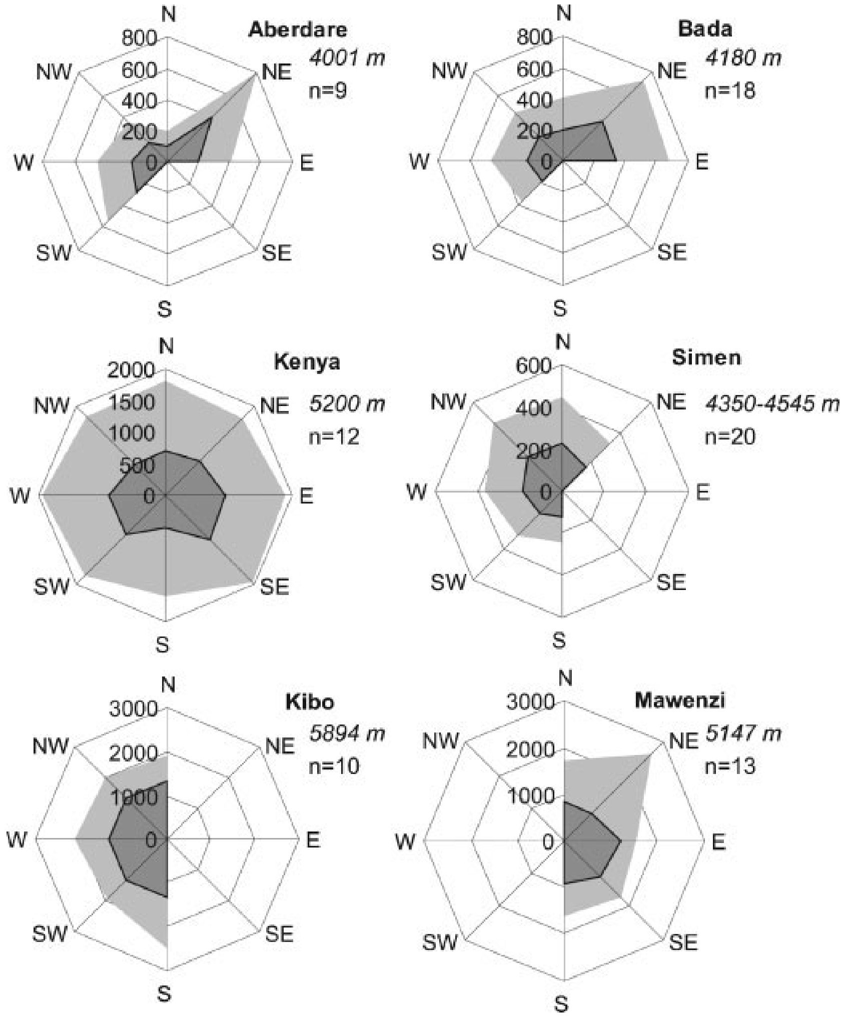

Figure 5 Radar plots of the vertical range (m) of (assumed) LGM glacial moraines (summit – moraine elevation) by aspect aggregated to eight principal directions for mountain localities. Dark shading is best estimate of ELA. The number of valley-specific palaeoglaciers (n) and maximum summit elevation (italics) are listed for each locality

Their results (Table 3) have instigated a radical reassessment of Mahaney's glacial sequence, including a reversal in relative ages of the main moraines. The Liki I moraines appear by ^{36}Cl dates to be the oldest glacial moraines on the mountain (estimated landform age of 355–420 ka), while results showed ages of 255–285 ka for the Teleki moraine in Teleki valley (Fig. 4). The Liki II and III are candidates for the LGM, although none of the landform ages cluster at 21 ka, as on Kibo. Instead, the Liki II moraines occur in different forms on either side of the mountain, with no clear moraine form and wide spread of ages from 19 ka to 130 ka on 10 boulder samples in Teleki valley, but a distinct crested moraine and an age of 28 ± 3 ka in the Georges valley. A number of low-relief, bouldery, inset moraines upvalley from Liki II in Georges valley merit a new subclass named Liki IIA by Shanahan and Zreda (2000), and two boulders yield an average age of 14.6 ± 1.2 ka. The Liki III comprise several closely spaced moraines at 4000 m, with boulders showing little erosion, and an age of 10.2 ± 0.5 ka. Similar to Liki II, the III stage features a substage, IIIA, with a large spread of ages comprising two groups (11.2 ± 0.8 and 8.6 ± 0.2 ka).

Moraine preservation is much better and more continuous for the Liki I glaciation, which correlates to the Younger of the original Baker map and was mapped by Hastenrath (1984) (red moraines in Fig. 6). Liki I moraines also became the basis of LGM ELA calculations, aggregated into eight cardinal aspect classes by Kaser and Osmaston (2002) and Osmaston and Harrison (2005). Using the existing moraine maps, 12 individual glacier valley extensions are identifiable, showing a pattern (Fig. 5) distinct from the present in that the SE is lower than NW and W aspects.

Rwenzori

Osmaston (1989b) proposed a relative chronology for three major Pleistocene glaciations in the Rwenzori based on glacial geological evidence (oldest to youngest): Katabura, Rwimi Basin and Mahoma. A single radiocarbon date from basal sediments in the small moraine-dammed Lake Mahoma provides a minimum age for the Mahoma glaciation of between 16 860 and 18 649 ^{14}C a BP (Livingstone, 1962), thus identifying it as a likely LGM position (Table 2). Notably the Mahoma lake core extended deeper, so the actual basal age was estimated to be 1250 ^{14}C a older (Livingstone, 1967), placing it even closer to the LGM. The oldest two stages were estimated to pre-date 100 ka (Fig. 4).

Osmaston also made an extensive analysis of the spatial distribution of individual former Mahoma-stage palaeoglaciers reconstructed from moraine maps, permitting statistically robust spatial interpretation of LGM ELAs. The Mahoma glaciation left very large moraines up to 150 m high and 5 km long, extending to different altitudes on all sides of the main peaks, but to a lowest altitude of 2000 m a.s.l. in the east

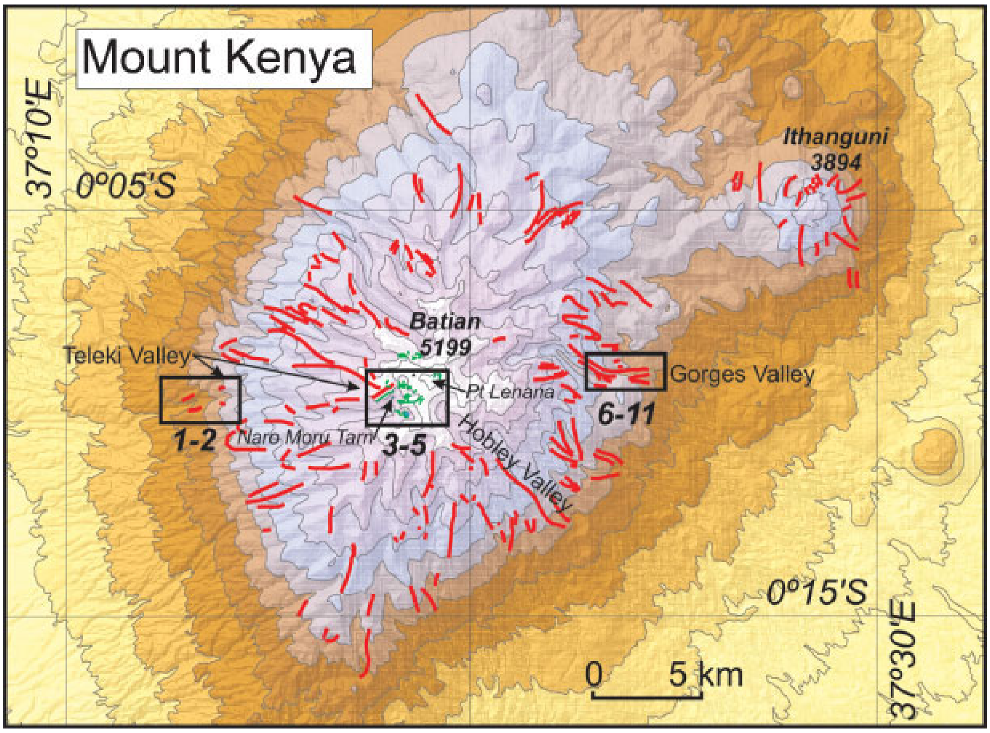

Figure 6 Hill-shaded map of Mount Kenya based on SRTM DEM, as explained in Methods section. Moraines mapped by Hastenrath (1984) and Shanahan and Zreda (2000) are in red and green (for Liki III, IIIA). Boxes show locations of CRN ages from Shanahan and Zreda (2000) numbered according to Table 3. Other locations and principal valleys mentioned in text are labelled, with summit elevations given in metres

(Osmaston, 2004). The extent and hypsometry of 75 individual palaeoglaciers were mapped on 1:50 000 contours, and ELAs computed using the Area × Altitude Balance Ratio (AABR) method (Osmaston, 1989b, 2005). The LGM ELA surface tilted generally to the east in the form of an elongated, tilted dome, reflecting the topography and dominant easterly wind, indicating a strong control on ELA by macro- and meso-scale climatic and relief factors (Osmaston, 2004). Additional analyses of change in ELA from LGM (ΔELA) to modern (Mark *et al.*, 2005) show a large amount of variation moderated by glacier aspect, with most variation (~70%) explained by headwall elevation (Fig. 7). The strong negative correlation between headwall elevation and ΔELA also supports a topographic influence on glacier–climate interaction, wherein basin morphometry modulates the response of individual glaciers to regional climate changes.

Table 5 Mount Kenya glaciations. Comparative key to glaciations discussed in text, referencing both Mahaney's work (1979, 1989, 1990, 2004) and the CRN dates of Shanahan and Zreda (2000)

Mahaney		Shanahan and Zreda		Valley (elev., m)
Glaciation	Age	Glaciation	Age	
Gorges	>1.9 Ma		6.5 ± 0.9 ka[a]	Gorges (~2850)
Lake Ellis	>780 ka			
Naro Moru	<730 ka		33–101 ka[a]	Gorges (3740)
Teleki	150–300 ka	Teleki	255–285 ka	(~3000)
(Liki)	MIS 2			(3200–3650)
Liki I	~50 ka	Liki I	355–420 ka	Gorges (3500)
Liki II	>25 ka	Liki II	19–130 ka	Teleki (3800)
		Liki II	28 ± 3 ka	Gorges (3500)
		Liki IIA	14.6 ± 1.2 ka	Gorges (3470)
Liki III	<12.5 ka	Liki III	10.2 ± 0.5 ka	Teleki (4150)
Liki IIIA	8.6 ± 0.2 ka	Teleki (4150)		
Tyndall	~1 ka			
Lewis	~0.1 ka			

[a] Considered equivocal landform.

The Omurubaho stage features a revision of nomenclature by Osmaston (1989b) for the (presumed) Holocene stage previously named Lac Noir – Lac Vert. The moraines marking this stage commonly occur in pairs and are generally located between 3600–4000 m, with the type site at Omurubaho at 3630 m. Earlier interpretations based on the fresh appearance of moraines were that these represented a glacier advance a few thousand years ago, but it is probable that they are closer to the Mahoma stage, and thus Lateglacial. They could be a small readvance or standstill. Individual palaeoglacier ELAs were computed and an ELA surface generated to show a similar spatial pattern to present, with ELAs falling from 4400 m on western exposure to 4060 m on the east. This gradient surface represented an estimated 250–300 m lowering from modern snowline (Osmaston, 1989b). There are no dates associated with these moraines. The near parallelism between the ELA trend surfaces of different glacial stages was noted to reflect a persistence through time in regional wind patterns, despite other proxy evidence suggesting changes in climate patterns through time (Osmaston, 2004).

As the only mountain massif in East Africa that is not volcanic, glaciations in the Rwenzori have been observed to be constrained by structure and erosion. Whittow (1966) recognised a fragmented summit planation surface that appears to have been critical for glacial history (Hastenrath, 1984). Evidence for the earliest glaciation, Katabura, exists exclusively on interfluves, and implies that the glaciation was more of an ice cap that did not conform to valley forms, as did the later glaciations (Kaser and Osmaston, 2002). Likewise, the intermediate aged Rwimi Basin glaciation is largely inferred by glacial erosion, since the depositional evidence is scarce to non-existent, but the overdeepened valleys subsequently occupied by relatively small Mahoma and later-stage moraines must have been eroded by an earlier event.

The Aberdare Mountains and Mount Elgon

Moraines presumed to be LGM were mapped by Hastenrath (1984) along a high volcanic ridge along the Eastern Rift called the Aberdare Mountains, or Nyandarua (e.g. Rosqvist, 1990) (Fig. 8). The evidence of full extent is equivocal, and imagery suggests there may have been a larger ice cap extending beyond the mapped moraines. There is an obvious asymmetry in the glacier extent, featuring largest extension to the NE, and a lack of any moraines to the SE (Fig. 5). The estimated correlative ELA would have been 100–400 m below the summit. A single radiocarbon date from the base of a cirque bog at 3800 m near the highest summit, Mt Satima (4002 m), yielded a minimum age of deglaciation of 12 200 ^{14}C a BP (Perrott, 1982) (Table 2). This is within the range to suggest LGM glaciation, although none of the moraines have been dated directly.

Mt Elgon (4320 m) is the largest solitary volcano in East Africa, with a caldera 8 km in diameter that contains cirque forms, moraines and valley profiles indicating glacier erosion (Fig. 9). Two radiocarbon dates from the basal sediments of Lake Kimilili at 4150 m indicate deglaciation by 11 973 and 13 188 ^{14}C a BP (Table 2). About 30 individual palaeoglaciers can be recognised descending around 400 m on all sides of the caldera, with the maximum descents and lowest palaeo-ELA estimates on the north side (Osmaston and Harrison, 2005). There is no positive evidence of earlier glaciation, but the relatively deep cirque forms hint at multiple glaciations, including post-LGM cirque deepening, although no earlier or later deposits have been identified (Hamilton and Perrott, 1979). Modern vegetation indicates an opposite precipitation gradient featuring much drier conditions to the north. It has been suggested that this reversal of presumed LGM precipitation and ELA gradient may be explained by either increased LGM NE trade winds, or the relatively drier winds from the desiccated Victoria Lake basin (Hamilton and Perrott, 1979).

Ethiopian plateau

The high volcanic plateau of central Ethiopia contains ten summits over 4000 m a.s.l., and at least three bear evidence of glaciation. Minimum dates have been recovered from each of these three, and moraines allow for the reconstruction of individual palaeoglaciers.

Simen Mountains

Twenty individual glacier catchments have been identified in the Simen Mountains, and the original maps allow for actual palaeoglaciers to be reconstructed, including moraine maps with termini and headwall elevations (Fig. 10) (Hurni, 1989). Radiocarbon dates have been recovered from ‘moor deposits on ground moraines’ in three catchments (on Analu, Mesarerya and Bwahit). The oldest is cited as sample B-3043 with age 4120 ± 90 ^{14}C a BP (Table 2). Hurni’s analysis includes a careful mapping of glacial and periglacial deposits, from which he infers that conditions required 7°C cooling and drier conditions (less precipitation and runoff), ‘with a tendency towards winter (November–March) precipitation, and only occasional summer (June–August) clouding with reduced or missing monsoons’. From this he assumes that the most probable age for this ‘last cold period of Simen’ was late Würm, 20–12 ka. He acknowledges the possibility of older glaciations, but recognised no obvious signs above 3000 m. Osmaston (unpublished field notes) observed moraine-like ridges 250 m below the terminus elevations documented by Hurni to as low as 3800 m. Earlier workers like Nilsson (1940) proposed that an older and more extensive glaciation reached as low as 2600 m, but no evidence has been verified to distinguish these features from periglacial or mass movement deposits (Osmaston and Harrison, 2005).

Bale Mountains

These mountains were visited during a 5-day survey in April 1976, and Late Pleistocene glacial evidence was studied in the highlands and tributary valleys (Messerli *et al.*, 1977; Hurni, 1989). The authors concluded that an ice cap of about 700 km^2 extended over the plateau, with individual outlet glaciers exceeding 250 m thickness and extending down to 3200 m near Goba town, with an ELA around 3700 m. The presence of forests on slopes, lakes and bogs in the Bale region currently results from a wetter climate than further north, and helped substantiate this initial interpretation that this site once featured the most extensive ice cap in Africa. Yet subsequent careful field mapping and aerial photography of the region found evidence for much reduced glaciation (<100 km^2), including a conspicuous moraine called the Big Boulder Moraine (BBM) from an ice cap around the high peak Tullu Dimtu (4380 m) of ~30 km^2 and ELA at 4230 m (Fig. 11) (Osmaston *et al.*, 2005).

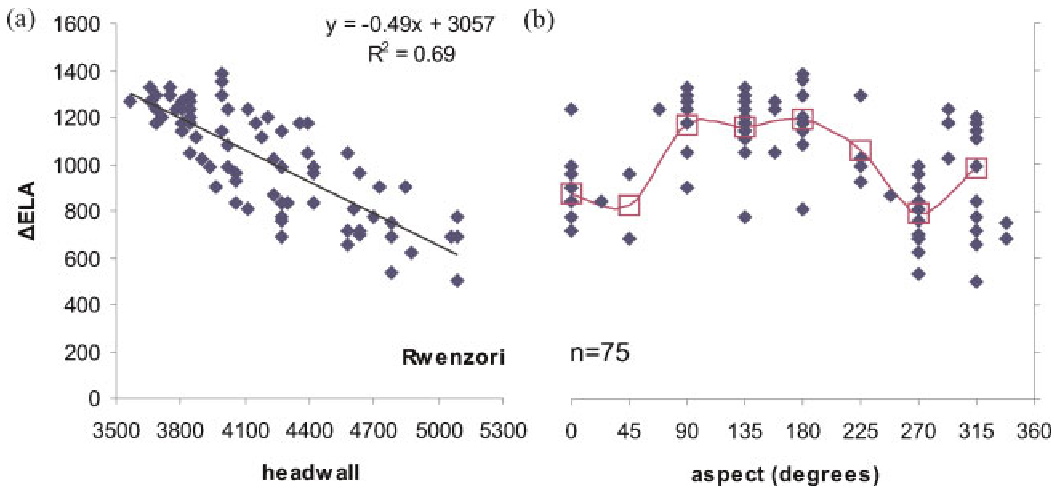

Figure 7 (a) Plot of change in ELA from LGM to present (ΔELA) with headwall elevation (m) for 75 reconstructed palaeoglaciers of the Rwenzori, showing extremely statistically significant ($P < 0.0001$) negative relationship. (b) Plot of ΔELA by aspect, with averages for each of eight primary compass directions shown with open squares, joined by line. This figure is available in colour online at www.interscience.wiley.com/journal/jqs

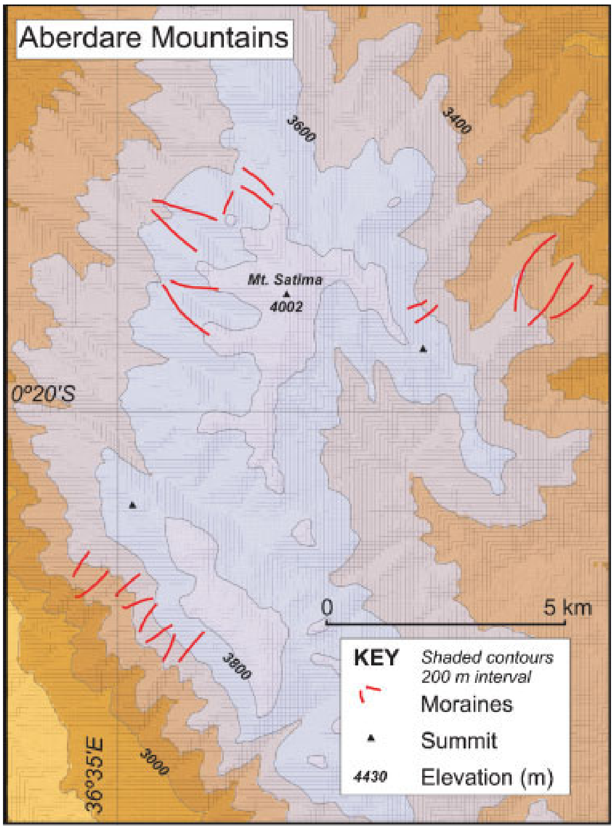

Figure 8 Aberdare Mountains, based on Hastenrath (1984). Figures 8–13: Site maps of mountain localities having evidence of glaciation constrained by absolute dates, with topography from SRTM DEM as explained in Methods. Moraines and other mapped features identified in keys based on published maps

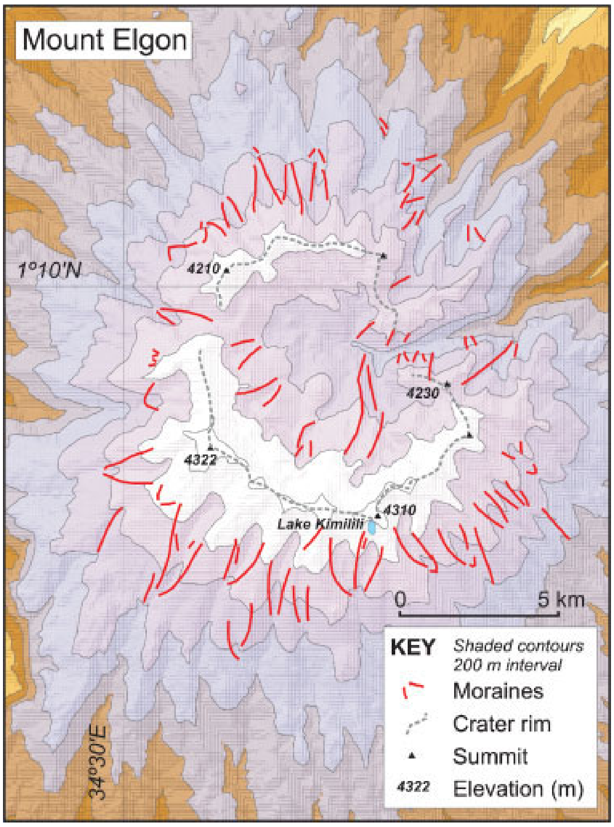

Figure 9 Mount Elgon, based on Hastenrath (1984), Kaser and Osmaston (2002), Osmaston (2004) and Osmaston and Harrison (2005), as modified from Hamilton and Perrott (1979)

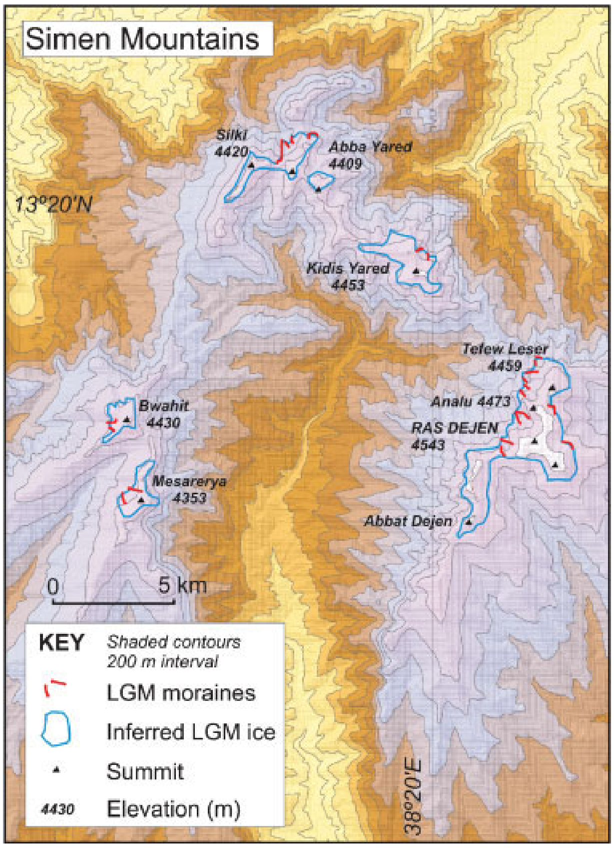

Figure 10 Simen Mountains, after Hurni (1989) and portrayed in Osmaston (2004) and Osmaston and Harrison (2005)

Moraines of different types exist on the plateau, and perhaps indicate different phases of glaciation. Also, distinct valley glaciers extended up to 7 km to the NE occupying well-defined valleys with roche moutonnées and moraines descending to 3400 m, suggesting an ELA of 3900 m. Periglacial features have

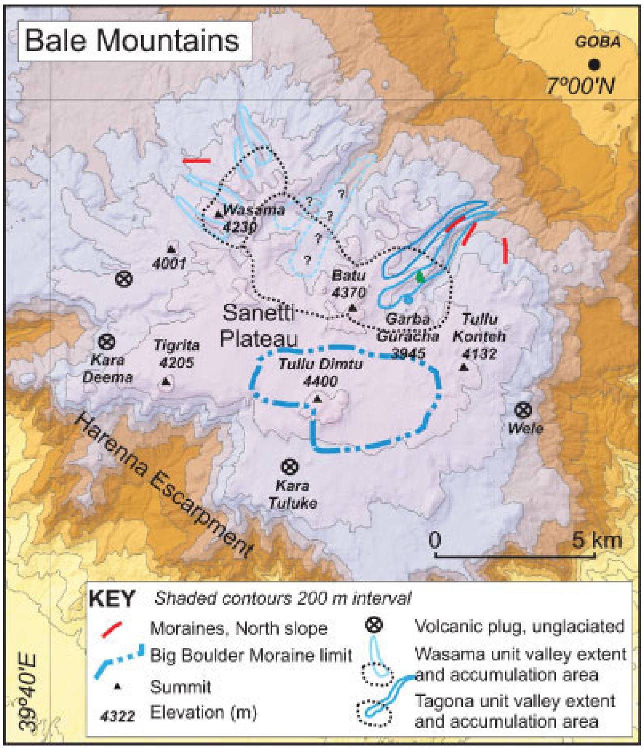

Figure 11 Bale Mountains, after Osmaston *et al.* (2005)

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been observed, but not mapped or described in detail (Grab, 2002). Unique grooved boulder slopes on the Sanetti Plateau just beyond the BBM limit at ~4000 m evidence persistent periglacial conditions, interpreted to have formed in a cold and dry climate. An older glaciation is also evidenced here by remnant moraines and erratics perched high above the northeastern valleys. Two radiocarbon dates in glaciated regions define minimum ages: a 16 m core from moraine-dammed Lake Garba Guracha (3950 m) at the head of the Togona Valley has a basal age of 13 950 ^{14}C a BP (Umer, cited by Osmaston and Harrison, 2005); another core 2.6 m long on the eastern edge of the plateau was dated to 15.6 ka ± 255 ^{14}C a BP (Table 2). Although the former date lacks age ranges to calibrate, the two ages are consistent. Another date of 14 ^{14}C ka BP from the base of an organic core at 3000 m in periglaciated terrain on the north slopes is interpreted as marking the beginning of deglaciation from the region (Mohammed and Bonnefille, 1998).

Mount Bada

Large terminal moraines between 3200 and 3700 m demarcate 18 palaeoglaciers of a glaciation named Boraluku (Potter, 1976; Street, 1979), constrained by a single minimum radiocarbon age of 11 500 ^{14}C a BP from a 3 m core from Bog 3 at 4040 m (Hamilton, 1982) (Fig. 12; Table 2). An estimated LGM ELA shows asymmetry, 3700 m on east and 3900 m on west (Osmaston and Harrison, 2005). Possible glacial erratics were observed much lower on slopes (Osmaston, unpublished field notes), but remain unconfirmed.

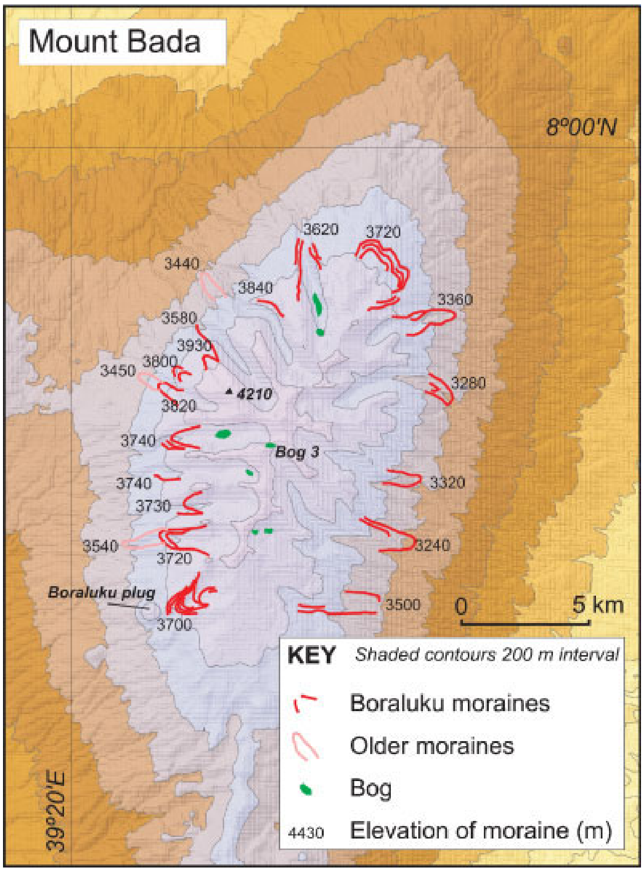

Figure 12 Mount Bada, after Osmaston and Harrison (2005), also in Osmaston (2004), based on aerial photography, ground reconnaissance and 1:50 000 maps from Street (1979)

Atlas Mountains, North Africa

The most recent reviews of the Atlas Mountains document that despite a lack of absolute dates abundant glacial and periglacial features evidence at least three discrete phases of glaciation, with spatial patterns reflecting climate gradients (Hughes *et al.*, 2004, 2006). Glacial features have been described on a number of peaks (Fig. 1): three peaks of the High Atlas (Jbel Toubkal, Irhil M'Goun and Jbel Ayachi); two in the Middle Atlas (Jbel Bou Naceur and Jbel Bou Iblane); and one in the Tell-Atlas (Djurdjura) (Osmaston and Harrison, 2005). Well-formed moraines are rare, but cirques, troughs, roche moutonnées, riegels and moraines have all been observed (Hughes *et al.*, 2004). For example, moraines and other features were mapped on the northern slopes around Irhil M'Goun (Wiche, 1953) (Fig. 13). Rock glaciers were also observed, though are likely relict debris rock glaciers positioned below cirque moraines in discontinuous permafrost (Hughes *et al.*, 2006). Well-developed glacial troughs have been observed on the S and SE slopes of Jbel Bou Iblane (Middle Atlas), despite a N to NW exposure to Atlantic moisture (Awad, 1963). This reflects the modern preference of deeper snow drifts to the leeward eastern sides by drifting, suggesting similar circulation patterns in the past.

Based on cirque floor elevations, Awad (1963) estimated a Quaternary snowline gradient lowering from S to N by ~200 m per degree latitude. LGM ELAs were calculated by other researchers using undocumented methods, presumably based on midpoint elevations, and summarised by Osmaston and Harrison (2005). The estimated ELAs rise toward the south and west from ~1900–2100 m in the Algerian Tell to 2400–2500 m in the Middle Atlas to over 3300 m in the High Atlas (Hughes *et al.*, 2006). This gradient is best explained by precipitation patterns, which reflect modern maxima near the Mediterranean Sea. Moreover, the gradient in LGM ELA was noted to be greater than extrapolations to modern ELAs (assumed as the 4.5°C mean annual isotherm), inviting a hypothesised stronger precipitation control on LGM glacier extent. Nonetheless, any climate interpretations are speculative given the lack of firm chronology on these features.

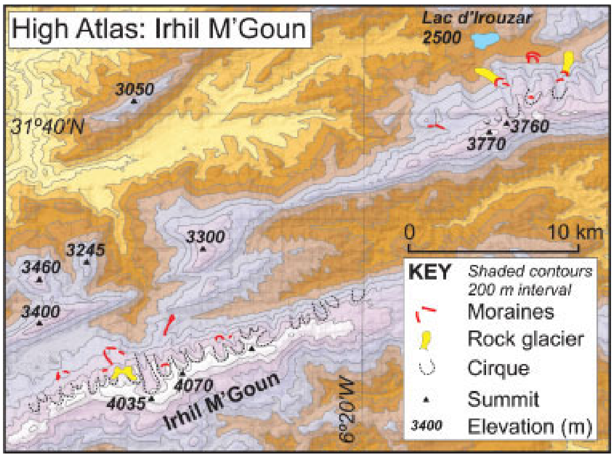

Figure 13 High Atlas, Irhil M'Goun, after Hughes *et al.* (2004), as derived from Wiche (1953)

The Drakensberg, South Africa

Numerous investigations over the past 50 years have been devoted to discerning whether these highlands were glaciated (Boelhouwers and Meiklejohn, 2002), and the most convincing sedimentary details have supported only very limited cirque glaciers at the highest elevations. Striated clasts in unconsolidated diamicts forming moraine-like ridges are suggestive of a very small glacier (0.05 km^2) that may have formed below Mt Enterprise (2565 m), near Elliot in the Eastern Cape Province of South Africa, during the LGM (Lewis and Illgner, 2001). This organic sediment is apparently reworked and considered to pre-date the glacier, which had an ELA at 2109 m, implying a cooling of $\sim$17°C, and was nourished by wind-drifted snow. The low organic carbon (0.08%) within a ridge yielded a single unreliable radiocarbon age close to infinite (>44 ^{14}C ka BP). Periglacial deposits in the vicinity suggest cooling of at least 10°C. A more impressive cirque moraine exists at Killmore ($\sim$2000 m), also in the East Cape Drakensberg. Although initially interpreted as a pro-talus rampart (Lewis, 1994), subsequent investigations concluded that a well-developed cirque moraine and pro-talus ramparts exist (Lewis and Illgner, 2001). Other work has reported only small cirque moraines on the highest mountains near the Lesotho–KwaZulu–Natal border (>3000 m), having LGM correlative ages (maximum of three dates = 17 300 ± 100 ^{14}C a BP) dated from soil organics (Mills and Grab, 2005). Using extrapolations from modern climate data to a curve showing modern glacier ELA climate (Ohmura *et al.*, 1992), the authors concluded that some limited glaciers could have been sustained with 5–7°C cooling more consistent with other proxies and modelling for the LGM (Partridge *et al.*, 1999; Mills *et al.*, 2007).

Discussion and interpretation

Available radiometric dates and recent refinement with CRN support a widespread glacial advance in synchrony with the latest maximum in global ice volume at the LGM. The Main glacial moraines represent the largest forms on Kilimanjaro, and have CRN dates that are solidly in MIS 2, very close to the LGM proper (20 ka). The mostly minimum ages on other mountains for correlative features, many close to the regional summit elevations, are not inconsistent with an LGM glaciation, but suggest deglaciation by about 16–17 ka. However, the CRN ages of Liki II moraines on Mt Kenya (28 ± 3 ka) suggest that the maximum extent since MIS 5e may have occurred close to 30 ka. The Liki IIA and III moraines upvalley have younger ages, signifying that either the LGM event persisted from an earlier onset, or was a less extensive event. A solitary, unweathered boulder on the saddle between Kibo and Mawenzi features a similar age (38 ka), and may represent the last time this part of the mountain was glacierised, implying a greater extent than the Main glaciation. This remains speculative, but the possibility of an older local LGM warrants additional CRN dates throughout Africa.

Additional sampling is also required to test hypothesised patterns of African glaciation prior to MIS 2, important in evaluating the sensitivity of low latitude regions to global boundary conditions. For example, Shanahan and Zreda (2000) have presented a hypothesis that MIS 6 moraines are absent, or at least smaller than MIS 2 and MIS 8–10 in tropical East Africa. This is contrary to what is generally observed or inferred elsewhere on a global scale. They have corroborated this interpretation with observations from three marine records: sapropel is seen in the Mediterranean during MIS 6, indicating interglacial conditions in East Africa; there is a lack of ice volume fingerprints in Arabian Sea sediments during MIS 6; alkenone SSTs are higher in MIS 6 than MIS 2 by up to 4.5°C (Zreda and Shanahan, 1999). The implication is that at such times the tropics are more impacted by regional or zonal factors like insolation than high-latitude boundary conditions.

Episodes of apparently synchronous glaciation throughout Africa invite a hypothesis that high northern latitude glacial boundary conditions hold predominance over low-latitude insolation in driving glaciation. Because orbital precession is in antiphase between hemispheres (Berger, 1978), the LGM would have featured insolation-enhanced monsoon precipitation in the southern African tropics. Yet a review of late Quaternary hydrology shows that the LGM was generally dry in both hemispheres, implicating a reduced vapour flux due to colder, glacial sea surface temperatures (SSTs) (Gasse, 2000). Records from East African lakes record a dry LGM, including the desiccation of Lake Victoria between 15 and 20 ka, while similar low lake levels were evident in Lake Bosumtwi in Ghana (Goudie, 1996). A review of multiproxy palaeoenvironmental records also shows that cool and dry conditions prevailed throughout East Africa during the LGM, although slightly warmer than a cold and dry period from 42 to 30 ka (Kiage and Liu, 2006). Still, this remains a controversial topic, as other records in the region have been interpreted to show wetter conditions at the LGM due to enhanced insolation-forced monsoon precipitation (Garcin *et al.*, 2006; Dupont *et al.*, 2007).

Climate modelling work has demonstrated that low-latitude African sites are highly sensitive to changes in high-latitude boundary conditions (deMenocal and Rind, 1993). Assimilation of model output with the palaeo-lake-level observations from southern East Africa has shown that lower SSTs and the presence of the Northern Hemisphere ice sheets must have been dominant over any monsoon precipitation rise caused by astronomically induced summer insolation enhancement in the southern African tropics (Barker and Gasse, 2003).

Other studies have hypothesised that the control of high-latitude Northern Hemisphere glacial conditions over African hydrology is actually variable over the Lateglacial–Holocene transition. It has been proposed that the relatively uniform response of mountain glaciers at the LGM was succeeded by much less spatially consistent Holocene activity as a result of local-scale hydrological variability (Olago, 2003). A 25 ka palaeoclimate reconstruction from Lake Malawi confirms a cool, dry LGM and even records a close correspondence with millennial-scale variability from Greenland ice cores (Johnson *et al.*, 2002). However, this close correlation breaks down in the Holocene, when Malawi displays more variability than the GRIP core, presumably because the inter-hemispheric linkages weakened with continental ice sheet demise. Similarly, lake-level history from Lake Bosumtwi suggests that tropical Africa is closely tied to Northern Hemisphere conditions from the LGM to the Younger Dryas, but that during warmer phases local–regional climate prevails (Shanahan *et al.*, 2006).

Comparisons between proxy records and the glacial chronology also invites hypotheses about the relative sensitivity of glaciers to temperature and precipitation. Accompanying a relatively dry LGM, a Lake Malawi biogenic proxy shows that continental temperatures were $\sim$3.5°C colder during the LGM, with other drops of $\sim$2°C at the Younger Dryas (12.5 ka) and 8.2 ka (Powers *et al.*, 2005). The Younger Dryas chron has been shown to feature arid conditions in East Africa (Roberts *et al.*, 1993). Uncertainties in the Liki III moraines on Mt Kenya make it possible they were coeval with such a global event (Shanahan and Zreda, 2000). The 8.6 ± 0.5 ka date for a Liki IIIA event is less certain, but invites further tests. Dry, cold periods of glaciation contrast with initial associations of African glaciations with pluvials (Nilsson, 1949), but also modern observations indicating aridity-driven ice loss (Mölg *et al.*, 2003b; Mölg and Hardy, 2004). Such complex and time-variable responses of glaciers to climate advocate for glacier-specific analyses, utilising multiple ELA reconstructions (i.e. Osmaston, 2005), inverse mass balance or ice flow modelling.

Higher-resolution proxy records from the Lateglacial and Holocene preserved in lakes provide evidence to test hypotheses of climate–glacier interactions on scales not resolved by discontinuous moraines. Diatom records of $\delta^{18}O$ from three tarns on the northeastern side of Mt Kenya, spanning 14 ^{14}C ka BP, are hypothesised to primarily reflect variations in moisture balance and cloud height, driven by SST anomalies (Barker *et al.*, 2001). The similarity in the three records reflects a regional climatic forcing modified by local hydrological factors. Four major negative shifts were observed that can be traced between basins: 11.6–8.6 ka; two abrupt minima between 6.7 and 5.6 ka; and 2.9–1.9 ka. They also suggest that anomalously heavy snowfall events recorded in diatom $\delta^{18}O$ contributed to Neoglacial ice advances inferred from lacustrine sediments and dated to $>$5.7 ka, 3.2–2.3 ka and 1.3–1.2 ka (Karlen *et al.*, 1999). Increased glacier meltwater contribution and temperatures up to 4°C warmer are inferred between 2.3 ka and 1.5 ka from biogenic opal in Mt Kenya's Hausberg tarn (Rietti-Shati *et al.*, 2000).

Clarifying the glacial sequence in the Atlas could aid in testing hypotheses related to gradients of humidity over time. On one hand, offshore marine pollen records from between Portugal and the Canary Islands indicate a progressive aridification of the Atlas Mountains over the past two glacial periods (250–5 ka), along with gradual northward progression of the Sahara (Hooghiemstra *et al.*, 2006). Alternatively, the sedimentary records from the Canary Islands and coastal regions of Morocco suggest a conceptual model featuring prevalence of westerlies, not the assumed intensified NNE trades at 18 ka (Rognon and CoudeGaussen, 1996). In this case, North Africa was not totally dry, but only a narrow cold/arid coastal belt prevailed because of cold North Atlantic SSTs, due to meltwater from the Northern Hemisphere ice sheets.

Comparison with tropical South America

From the only other continent spanning the Equator, Andean glacial history provides an intriguing comparison with records in Africa, especially since the widespread application of CRN dating. A few observations of similarities are provided here for the tropical regions, the only region with absolute ages in both continents. First of all, both regions feature evidence of multiple glaciations, with at least one episode pre-dating the LGM. In most sites, the older glaciations appear to have had larger extensions of glaciers, with the notable Andean exception of Bolivia (Smith *et al.*, 2005). Secondly, the possibly earlier maximum extent during the last glacial cycle noted above in East Africa has also been suggested for the tropical Central Andes, where CRN dates on moraines (Smith *et al.*, 2005) indicate that a larger glacier advance pre-dates the LGM. There are still too many uncertainties in the CRN methodology to make more precise evaluations of this timing, but the pattern is suggestive of global forcing. Similarly, a comparison can be tentatively drawn between the Lateglacial events noted in the Andes (widely dated 18–15 ka, Smith *et al.*, this volume) and East Africa, specifically the Omurubaho and Liki IIA stages. Evidence for an advance correlative with the Younger Dryas chron has been documented in both continents, but the evidence is equivocal. Finally, while general patterns suggest global-scale pacing of glacial events, local controls of topography and climatic gradients have been observed to control glacier extent in both continents (Smith *et al.*, this volume, 2005; Mark *et al.*, 2005; Kaser and Osmaston, 2002).

Conclusions and future work

Evidence for Quaternary glaciation existing on discrete mountain highlands spanning $>40^{\circ}$ latitude across Africa has been observed since the 19th century but remains understudied and poorly dated. Furthermore, as a general statement for the continent, all palaeoclimate implications must remain provisional in the absence of improved absolute dates. Nine mountain localities have absolute dates, but only two feature highest ranked dating method control featuring direct CRN ages from moraines (Table 1). Other regions feature strong evidence of glaciation, but lack dates (Atlas, Ithanguni) or have more equivocal glacial evidence (Drakensberg). These should be considered priority sites for future CRN.

A single published chronological work featuring CRN in East Africa makes this the best-dated region in Africa, and demonstrates either confirmation of previously accepted glacial sequences (Kibo and Mawenzi) or a radical reinterpretation of Quaternary glaciations (Mt Kenya). The CRN dates confirm previously documented glaciations pre-dating the LGM, and seemingly associate the oldest with MIS 12 or older. While the apparent LGM at MIS 2 fits the global ice volume records, some dates suggest an actual maximum extent for equatorial Mt Kenya at $\sim$30 ka, pre-dating the global LGM. An apparent lack of distinct MIS 6 moraines indicates a relatively smaller glacier extent than MIS 2, suggesting a decoupling in low-latitude climate response from that of higher latitudes, where glaciers had larger responses at MIS 6 (Shanahan and Zreda, 2000). However, more samples should be recovered to test this. Given the detail available to reconstruct many individual palaeoglacier ELAs ($n=78$) in the Rwenzori, this should be a priority site for future CRN dating.

Minimum ages of deglaciation indicate possible synchrony of glaciation in the tropics to subtropics both north and south of the Equator at the LGM, implying that high-latitude boundary conditions reduced temperatures and predominated over insolation-driven monsoon precipitation forcing. Chronological similarity with Andean sites also strongly implicates global controls over glaciation.

However, the CRN dates provide strong evidence that the most extensive glaciation in East Africa was $>$360 ka. This much older pre-LGM glaciation calls into question the assumption that the glacial landforms in the Ethiopian highlands, Elgon and Aberdare are all LGM and not earlier. Furthermore, since the Liki I moraines are so well defined, and more extensive than the diminutive II and III, why are older glaciations not more extensive elsewhere? It thus seems an important priority to reassess all currently mapped Liki and Teleki moraines and to obtain more dates. Specifically, it is recommended that Ithanguni be visited, which is slightly lower than Batian but has mapped moraines.

The apparent inversion implied by CRN in East Africa indicates the need to better couple dating with careful stratigraphy. Geomorphological evidence shows that glacier form has changed over time. Erosion of valleys tends to abandon older tills on interfluves, and even results in situations where younger events extend further downvalley in more

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incised channels, while lateral moraines remain inset to older, preserved moraines.

There is a need to apply careful field mapping to accurately interpret and delimit palaeoglacier extensions, and ultimately simulate them with inverse models. The future should involve a return to the classic art of careful landscape descriptions and multi-proxy observations, but include state-of-the-art GPS mapping, satellite remote sensing and terrain analyses. The incorporation of standardised data on individual glacier localities is crucial to better integrate climate modelling (i.e. Mark *et al.*, 2005).

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References

Awad H. 1963. Some aspects of the geomorphology of Morocco related to the Quaternary climate. *Geographical Journal* **129**: 129–139.

Baker BH. 1967. *Geology of the Mt. Kenya area*. Geological Survey of Kenya: Nairobi.

Baker BH, Mohr PA, Williams LAJ. 1972. *Geology of the Eastern Rift system of Africa*. Special Paper, Geological Society of America: Boulder, CO.

Barker P, Gasse F. 2003. New evidence for a reduced water balance in East Africa during the Last Glacial Maximum: implication for model-data comparison. *Quaternary Science Reviews* **22**: 823–837.

Barker PA, Street-Perrott FA, Leng MJ, Greenwood PB, Swain DL, Perrott RA, Telford RJ, Ficken KJ. 2001. A 14,000-year oxygen isotope record from diatom silica in two alpine lakes on Mt. Kenya. *Science* **292**: 2307–2310.

Berger AL. 1978. Long-term variations in daily insolation and Quaternary climatic changes. *Journal of Atmospheric Sciences* **35**: 2362–2367.

Boelhouwers JC, Meiklejohn KI. 2002. Quaternary periglacial and glacial geomorphology of southern Africa: review and synthesis. *South African Journal of Science* **98**: 47–55.

Bradley RS. 1999. *Paleoclimatology: Reconstructing Climates of the Quaternary*. Academic Press: Boston, MA.

Bradley RS, Vuille M, Diaz HF, Vergara W. 2006. Threats to water supplies in the tropical Andes. *Science* **312**: 1755–1756.

Cerling TE, Craig H. 1994. Geomorphology and in-situ cosmogenic isotopes. *Annual Review of Earth and Planetary Sciences* **22**: 273–317.

Charsley TJ. 1989. Composition and age of older outwash deposits along the northwestern flank of Mount Kenya. In *Quaternary and Environmental Research on East African Mountains*, Mahaney WC (ed.). A. A. Balkema: Rotterdam; 165–174.

deMenocal PB. 1995. Pliopleistocene African climate. *Science* **270**: 53–59.

deMenocal PB, Rind D. 1993. Sensitivity of Asian and African climate to variations in seasonal insolation, glacial ice cover, sea-surface temperature, and Asian orography. *Journal of Geophysical Research-Atmospheres* **98**: 7265–7287.

Downie C. 1964. Glaciations of Mount Kilimanjaro northeast Tanganyika. *GSA Bulletin* **75**: 1–16.

Dupont LM, Behling H, Jahns S, Marret F, Kim JH. 2007. Variability in glacial and Holocene marine pollen records offshore from west southern Africa. *Vegetation History and Archaeobotany* **16**: 87–100.

Flint RF. 1959. Pleistocene climates in eastern and southern Africa. *Bulletin of the Geological Society of America* **70**: 343–374.

Garcin Y, Williamson D, Taieb M, Vincens A, Mathe PE, Majule A. 2006. Centennial to millennial changes in maar-lake deposition during the last 45,000 years in tropical Southern Africa (Lake Masoko, Tanzania). *Palaeogeography, Palaeoclimatology, Palaeoecology* **239**: 334–354.

Gasse F. 2000. Hydrological changes in the African tropics since the Last Glacial Maximum. *Quaternary Science Reviews* **19**: 189–211.

Gosse JC, Phillips FM. 2001. Terrestrial in situ cosmogenic nuclides: theory and application. *Quaternary Science Reviews* **20**: 1475–1560.

Goudie AS. 1996. Climate: past and present. In *The Physical Geography of Africa*, Adams WM, Goudie AS, Orme AR (eds.) Oxford University Press: Oxford; 35–59.

Grab S. 2002. Glacial and periglacial phenomena in Ethiopia: a review. *Permafrost and Periglacial Processes* **13**: 71–76.

Gregory JM. 1894. The glacial geology of Mount Kenya. *Quarterly Journal of the Geological Society* **50**: 515–530.

Hamilton AC. 1982. *Environmental History of East Africa: A Study of the Quaternary*. Academic Press: London.

Hamilton A, Perrott A. 1978. Date of deglacierization of Mount Elgon. *Nature* **273**: 49.

Hamilton AC, Perrott RA. 1979. Aspects of the glaciation of Mt. Elgon, East Africa. *Palaeoecology of Africa* **11**: 153–161.

Hastenrath S. 1984. *The Glaciers of Equatorial East Africa*. Riedel: Dordrecht.

Hastenrath S. 2001. Variations of East African climate during the past two centuries. *Climatic Change* **50**: 209–217.

Hastenrath S. 2006. Diagnosing the decaying glaciers of equatorial East Africa. *Meteorologische Zeitschrift* **15**: 265–271.

Hastenrath S, Kruss PD. 1992. The dramatic retreat of Mount Kenya's glaciers between 1963 and 1987: greenhouse forcing. *Annals of Glaciology* **16**: 127–133.

Holmgren K. 1987. Dating of a moraine on Mount Kenya–Reply. *Geografiska Annaler* **A69**: 365.

Hooghiemstra H, Lezine AM, Leroy SAG, Dupont L, Marret F. 2006. Late Quaternary palynology in marine sediments: a synthesis of the understanding of pollen distribution patterns in the NW African setting. *Quaternary International* **148**: 29–44.

Hughes PD, Gibbard PL, Woodward JC. 2004. Quaternary glaciation in the Atlas Mountains, North Africa. In *Quaternary Glaciation: Extent and Chronology*. Vol. 3: *Asia, Latin America, Africa, Australia, Antarctica*, Ehlers J, Gibbard PL (eds). Elsevier: Amsterdam; 255–260.

Hughes PD, Woodward JC, Gibbard PL. 2006. Quaternary glacial history of the Mediterranean mountains. *Progress in Physical Geography* **30**: 334–364.

Humphries DW. 1972. Glaciology and glacial history. In *The Geology of Kilimanjaro*, Downie C, Wilkinson P (eds). University of Sheffield: Sheffield; 33–71.

Hurni H. 1989. Late Quaternary of Simen and other mountains in Ethiopia. In *Quaternary and Environmental Research on East African Mountains*, Mahaney WC (ed.). A. A. Balkema: Rotterdam; 105–120.

Johansson L, Holmgren K. 1985. Dating of a moraine on Mount Kenya. *Geografiska Annaler* **A67**: 123–128.

Johnson TC, Brown ET, McManus J, Barry S, Barker P, Gasse F. 2002. A high-resolution paleoclimate record spanning the past 25,000 years in southern East Africa. *Science* **296**: 113–132.

Karlen W, Fastook JL, Holmgren K, Malmstrom M, Matthews JA, Odada E, Risberg J, Rosqvist G, Sandgren P, Shemesh A, Westerberg LO. 1999. Glacier fluctuations on Mount Kenya since similar to 6000 cal. years BP: implications for Holocene climatic change in Africa. *Ambio* **28**: 409–418.

Kaser G, Osmaston HA. 2002. *Tropical Glaciers*. Cambridge University Press: Cambridge, UK.

Kaser G, Hardy DR, Mölg T, Bradley RS, Hyera TM. 2004. Modern glacier retreat on Kilimanjaro as evidence of climate change: observations and facts. *International Journal of Climatology* **24**: 329–339.

Kiage LM, Liu KB. 2006. Late Quaternary paleoenvironmental changes in East Africa: a review of multiproxy evidence from palynology, take sediments, and associated records. *Progress in Physical Geography* **30**: 633–658.

Lal D. 1991. Cosmic-ray labeling of erosion surfaces - insitu nuclide production-rates and erosion models. *Earth and Planetary Science Letters* **104**: 424–439.

Lewis CA. 1994. Protalus ramparts and the altitude of the local equilibrium-line during the Last Glacial stage in Bokspruit, East Cape Drakensberg, South Africa. *Geografiska Annaler Series a: Physical Geography* **76**: 37–48.

Lewis CA, Illgner PM. 2001. Late quaternary glaciation in southern Africa: moraine ridges and glacial deposits at Mount Enterprise in the Drakensberg of the Eastern Cape Province, South Africa. *Journal of Quaternary Science* **16**: 365–374.

Livingstone DA. 1962. Age of deglaciation in the Ruwenzori Range Uganda. *Nature* **194**: 137–139.

Livingstone DA. 1967. Postglacial vegetation of the Ruwenzori Mountains in equatorial Africa. *Ecological Monographs* **37**: 25–52.

Livingstone DA. 1975. Late Quaternary climatic change in Africa. *Annual Review of Ecology and Systematics* **6**: 249–280.

Mahaney WC. 1979. Quaternary stratigraphy of Mt. Kenya: a reconnaissance. *Palaeoecology of Africa* **10/11**: 163–170.

Mahaney WC. 1987. Dating of a moraine on Mount Kenya–Discussion. *Geografiska Annaler* **A69**: 359–363.

Mahaney WC. 1989. *Quaternary and Environmental Research on East African Mountains*. A. A. Balkema: Rotterdam; 483.

Mahaney WC. 1990. *Ice on the Equator: Quaternary geology of Mount Kenya*. Wm Caxton: Sister Bay, WI.

Mahaney WC. 2004. Quaternary glacial chronology of Mount Kenya massif. In *Quaternary Glaciations: Extent and Chronology*, Part III Vol. 2, Ehlers J, Gibbard PL (eds). Elsevier: Amsterdam; 227–231.

Mahaney WC, Harmsen R, Spence JR. 1991. Glacial–interglacial cycles and development of the Afroalpine ecosystem on East African mountains: 1. Glacial and postglacial geological record and paleoclimate of Mount Kenya. *Journal of African Earth Sciences* **12**: 506–512.

Mark BG. 2002. Hot ice: glaciers in the tropics are making the press. *Hydrological Processes* **16**: 3297–3302.

Mark BG, Harrison SP, Spessa A, New M, Evans DJA, Helmens KF. 2005. Tropical snowline changes at the last glacial maximum: a global assessment. *Quaternary International* **138–139**: 168–201.

Messerli B, Winiger M. 1992. Climate, environmental change, and resources of the African mountains from the Mediterranean to the Equator. *Mountain Research and Development* **12**: 315–336.

Messerli B, Hurni H, Kienholz H, Winiger M. 1977. Bale Mountains, the largest Pleistocene mountain glacier system of Ethiopia. In *INQUA abstracts*, Birmingham, UK; 300.

Meyer H. 1890. *Ostafrikanische Gletscherfahrten*. Duncker & Humbolt: Leipzig.

Mills SC, Grab SW. 2005. Debris ridges along the southern Drakensberg escarpment as evidence for Quaternary glaciation in southern Africa. *Quaternary International* **129**: 61–73.

Mills SC, Carr SJ, Grab SW. 2007. Testing the feasibility of past glaciation in eastern Lesotho using glacier reconstruction approaches. In Papers presented at the 2007 INQUA Congress. *Quaternary International* **167–168**: 283–284.

Mohammed MU, Bonnefille R. 1998. A late Glacial/late Holocene pollen record from a highland peat at Tamsaa, Bale Mountains, south Ethiopia. *Global and Planetary Change* **16–17**: 121–129.

Mölg T, Hardy DR. 2004. Ablation and associated energy balance of a horizontal glacier surface on Kilimanjaro. *Journal of Geophysical Research – Atmospheres* **109**, D16104, doi: 1029/2003JD004338.

Mölg T, Georges C, Kaser G. 2003a. The contribution of increased incoming shortwave radiation to the retreat of the Rwenzori glaciers, East Africa, during the 20th century. *International Journal of Climatology* **23**: 291–303.

Mölg T, Hardy DR, Kaser G. 2003b. Solar-radiation-maintained glacier recession on Kilimanjaro drawn from combined ice-radiation geometry modeling. *Journal of Geophysical Research – Atmospheres* **108**(D23), 4731, doi: 10.1029/2003JD003546.

Mölg T, Rott H, Kaser G, Fischer A, Cullen NJ. 2006. Comment on 'Recent glacial recession in the Rwenzori Mountains of East Africa due to rising air temperature' by Richard G. Taylor, Lucinda Mileham, Callist Tindimugaya, Abushen Majugu, Andrew Muwanga, and Bob Nakileza. *Geophysical Research Letters* **33**, L20404, doi: 10.1029/2006GL02754.

Nicholson S. 1996. A review of climate dynamics and climate variability in Eastern Africa. In *The Limnology, Climatology and Paleoclimatology of East African Lakes*, Johns TC, Odada E (eds). Gordon & Breach: Amsterdam; 25–56.

Nicholson SE. 2000. The nature of rainfall variability over Africa on time scales of decades to millennia. *Global and Planetary Change* **26**: 137–158.

Nicholson SE, Kim E. 1997. The relationship of the El Nino Southern oscillation to African rainfall. *International Journal of Climatology* **17**: 117–135.

Nicholson SE, Selato JC. 2000. The influence of La Nina on African rainfall. *International Journal of Climatology* **20**: 1761–1776.

Nilsson E. 1931. Quaternary glaciations and pluvial lakes in British East Africa. *Geografiska Annaler* **13**: 249–349.

Nilsson E. 1935. Traces of ancient changes of climate in East Africa. *Geografiska Annaler* **1/2**: 1–21.

Nilsson E. 1940. Ancient changes of climate in British East Africa and Abyssinia. *Geografiska Annaler* **22**: 1–79.

Nilsson E. 1949. The pluvials of East Africa: an attempt to correlate Pleistocene changes of climate. *Geografiska Annaler* **31**: 204–211.

Nishizumi K, Kohl CP, Arnold JR, Dorn R, Klein J, Fink D, Middleton R, Lal D. 1993. Role of in-situ cosmogenic nuclides Be-10 and Al-26 in the study of diverse geomorphic processes. *Earth Surface Processes and Landforms* **18**: 407–425.

Ohmura A, Kasser P, Funk M. 1992. Climate at the equilibrium line of glaciers. *Journal of Glaciology* **38**: 397–411.

Olago DO. 2001. Vegetation changes over palaeo-time scales in Africa. *Climate Research* **17**: 105–121.

Olago DO. 2003. The paleo-climate record of mountain glaciers in equatorial Africa: a multi-millennium perspective on drought and implications for the future. In *Proceedings, CLIVAR/PAGES/IPCC*, Tucson, AZ; 7.

Osmaston HA. 1965. The past and present climate and vegetation of Ruwenzori and its neighbourhood. DPhil thesis, University of Oxford.

Osmaston H. 2004. Quaternary glaciations in the East African mountains. In *Quaternary Glaciations: Extent and Chronology*, Part III Vol. 2, Ehlers J, Gibbard PL (eds.) Elsevier: Amsterdam; 151–164.

Osmaston HA. 1989a. Glaciers, glaciations and equilibrium line altitudes on Kilimanjaro. In *Quaternary and Environmental Research on East African Mountains*, Mahaney WC (ed.). A.A. Balkema: Rotterdam; 7–30.

Osmaston HA. 1989b. Glaciers, glaciations and equilibrium line altitudes on the Ruwenzori. In *Quaternary and Environmental Research on East African Mountains*, Mahaney WC (ed.). A.A. Balkema: Rotterdam; 31–104.

Osmaston HA. 2005. Estimates of glacier equilibrium line altitudes by the Area × Altitude, the Area × Altitude Balance Ratio and the Area - × Altitude Balance Index methods and their validation. *Quaternary International* **138–139**: 22–31.

Osmaston HA, Harrison SP. 2005. The late Quaternary glaciation of Africa: a regional synthesis. *Quaternary International* **138**: 32–54.

Osmaston HA, Mitchell WA, Osmaston JAN. 2005. Quaternary glaciation of the Bale Mountains, Ethiopia. *Journal of Quaternary Science* **20**: 593–606.

Partridge TC, Scott L, Hamilton JE. 1999. Synthetic reconstructions of southern African environments during the Last Glacial Maximum (21-18 kyr) and the Holocene Altithermal (8-6 kyr). *Quaternary International* **57/58**: 207–214.

Perrott RA. 1982. A postglacial pollen record from Mt. Satima, Aberdare Range, Kenya. In *American Quaternary Association 7th Conference (AMQUA)*; 153.

Porter SC. 2001. Snowline depression in the tropics during the Last Glaciation. *Quaternary Science Reviews* **20**: 1067–1091.

Potter EC. 1976. Pleistocene glaciation in Ethiopia: new evidence. *Journal of Glaciology* **17**: 148–150.

Powers LA, Johnson TC, Werne JP, Castanada IS, Hopmans EC, Damste JSS, Schouten S. 2005. Large temperature variability in the southern African tropics since the Last Glacial Maximum. *Geophysical Research Letters* **32**, L08706, doi: 10.1029/2004GL022014, 2005.

Reimer PJ, Baillie MGL, Bard E, Bayliss A, Beck JW, Bertrand CJH, Blackwell PG, Buck CE, Burr GS, Cutler KB, Damon PE, Edwards RL, Fairbanks RG, Friedrich M, Guilderson TP, Hogg AG, Hughen KA, Kromer B, McCormac G, Manning S, Ramsey CB, Reimer RW, Remmele S, Southon JR, Stuiver M, Talamo S, Taylor FW, van der

Plicht J, Weyhenmeyer CE. 2004. IntCal04 terrestrial radiocarbon age calibration,0-26cal kyr BP. *Radiocarbon* **46**: 1029–1058.

Rietti-Shati M, Yam R, Karlen W, Shemesh A. 2000. Stable isotope composition of tropical high-altitude fresh-waters on Mt. Kenya, Equatorial East Africa. *Chemical Geology* **166**: 341–350.

Roberts N, Taieb M, Barker P, Damnati B, Icole M, Williamson D. 1993. Timing of the Younger Dryas Event in East-Africa from lake-level changes. *Nature* **366**: 146–148.

Rognon P, CoudeGaussen G. 1996. Paleoclimates off northwest Africa (28°–35° N) about 18,000 yr BP based on continental eolian deposits. *Quaternary Research* **46**: 118–126.

Rosqvist G. 1990. Quaternary glaciations in Africa. *Quaternary Science Reviews* **9**: 281–297.

Shanahan TM, Zreda M. 2000. Chronology of quaternary glaciations in East Africa. *Earth and Planetary Science Letters* **177**: 23–42.

Shanahan TM, Overpeck JT, Wheeler CW, Beek JW, Pigati JS, Talbot MR, Scholz CA, Peck J, King JW. 2006. Paleoclimatic variations in West Africa from a record of late Pleistocene and Holocene lake level stands of Lake Bosumtwi, Ghana. *Palaeogeography, Palaeoclimatology, Palaeoecology* **242**: 287–302.

Smith JA, Seltzer GO, Farber DL, Rodbell DT, Finkel RC. 2005. Early local last glacial maximum in the tropical Andes. *Science* **308**: 678–681.

Street FA. 1979. *Late Quaternary lakes in the Ziway-Shala basin, southern Ethiopia*. DPhil thesis, University of Oxford.

Street-Perrott FA, Huang YS, Perrott RA, Eglinton G, Barker P, Ben-Khelifa L, Harkness DD, Olago DO. 1997. Impact of lower atmospheric carbon dioxide on tropical mountain ecosystems. *Science* **278**: 1422–1426.

Stuiver M, Reimer PJ. 1993. Extended ^{14}C database and revised CALIB radiocarbon calibration program. *Radiocarbon* **35**: 215–230.

Summerfield MA. 1996. Tectonics, geology and long-term landscape development. In *The Physical Geography of Africa*, Adams WM, Goudie AS, Orme AR (eds.) Oxford University Press: Oxford; 1–17.

Taylor RG, Mileham L, Tindimugaya C, Majugu A, Nakileza B, Muwanga A. 2006a. Recent deglaciation in the Rwenzori Mountains of East Africa due to rising air temperature. *Geophysical Research Letters* **33**, L10402, doi: 10.1029/2006GL025962.

Taylor RG, Mileham L, Tindimugaya C, Majugu A, Nakileza B, Muwanga A. 2006b. Reply to comment by T. Mölg et al. on 'Recent deglaciation in the Rwenzori Mountains of East Africa due to rising air temperature'. *Geophysical Research Letters* **33**, L20405, doi: 1029/2006GL027606.

Thompson LG, Mosley-Thompson E, Davis ME, Henderson KA, Brecher HH, Zagorodnov VS, Mashiotta TA, Lin PN, Mikhalenko VN, Hardy DR, Beer J. 2002. Kilimanjaro ice core records: evidence of Holocene climate change in tropical Africa. *Science* **298**: 589–593.

Thompson LG, Mosley-Thompson E, Brecher H, Davis M, Leon B, Les D, Lin PN, Mashiotta T, Mountain K. 2006. Abrupt tropical climate change: Past and present. *Proceedings of the National Academy of Sciences USA* **103**: 10536–10543.

Trewartha GT. 1981. *The Earth's Problem Climates*. University of Wisconsin Press: Madison, WI.

Whittow JB. 1966. The landforms of the Central Ruwenzori, East Africa. *Geographical Journal* **132**: 32–42.

Whittow JB, Shepherd A, Goldthorpe JE, Temple PH. 1963. Observations on the glaciers of the Ruwenzori. *Journal of Glaciology* **4**: 581–616.

Wiche K. 1953. Klimamorphologische und talgeschictliche Studien im M'Goungebiet. *Mitteilungen der Geographischen Gesellschaft Wien* **95**: 4–41.

Zreda M, Shanahan T. 1999. Relative extents of the Penultimate and the Last Glacial Maxima in the Tropics. In *AGU Fall Meeting*, American Geophysical Union, San Francisco, CA.

Zreda MG, Phillips FM. 1995. Insights into alpine moraine development from cosmogenic Cl-36 buildup dating. *Geomorphology* **14**: 149–156.