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Palynological evidence for abrupt climatic cooling in equatorial Africa at about 43,000–40,000 cal BP

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ABSTRACT

The same basal sequence of two pollen zones is found in three previously published pollen diagrams for widely separated sites situated along highlands adjacent to the Albertine Rift in equatorial Africa. Here evidence is presented that is supportive of the hypothesis that the transition between the zones was contemporaneous at all sites and dates to about 43,000–40,000 cal BP. Environmental interpretation of the sequence indicates that there was a major fall in temperature, depressed temperature thereafter persisting until the transition to the postglacial at 14,000–11,500 cal BP. The climate also became drier. Well-dated sediments of this age are rare in equatorial Africa, so comparisons are scarce. However, there is some evidence from the Eastern Arc Mountains, Tanzania, of a similar climatic event at about the same time. Farther afield, there is good evidence for abrupt climatic deterioration at ~40,000 cal BP in western Eurasia, where there was accompanying cultural change. Sedimentary basins along the Albertine Rift-margin highlands are especially well suited for palynologically-based investigations of past temperatures. Their relatively well-defined catchment areas result in reduced inputs of pollen derived from vegetation growing under different climatic conditions.

1. Introduction

Attention is directed at a major change in vegetation from moist lower montane forest or *Syzygium* swamp forest (Forest Zone 1) to vegetation with abundant *Cliffortia nitidula* (*Cliffortia* Zone) apparent in previously published pollen diagrams from three widely separated sites in Uganda, Rwanda and Burundi (Hamilton, 1982; Bonnefille and Riollet, 1988; Taylor, 1990). *Cliffortia nitidula* R.E. and T.C.E. Fries, the only East African species of the genus, is a shrub typical of the Ericaceous Belt. A major change in climate has previously been inferred for each site separately, but what has not been recognised earlier is that the dating evidence is consistent with the hypothesis that the climatic events recognised for each site were contemporaneous (dating to sometime between ca. 43,000 and 40,000 cal BP). A major climatic event is indicated, possibly having major environmental impacts over an extensive area.

Very few sediment sequences containing well preserved pollen of this age are known from eastern Africa, hence the ability to identify contemporaneous climatic changes in neighbouring sites is rare. The topographic contexts of the sites are particularly appropriate for identifying temperature changes from pollen diagrams, because all are in valleys situated within a belt of highlands stretching along the eastern margin of the Albertine Rift, the total altitudinal ranges of their catchments or immediate neighbourhoods being relatively limited. This contrasts with some lowland lakes or sites of sediment accumulation on taller mountains, into which considerable quantities of pollen can be transported from vegetation growing under environments markedly different from those that prevail near the sample sites. This complicates assessments of past temperatures.

The three sites, all peat-forming systems associated with the Albertine Rift in central Africa, are Muchoya Swamp (2260 m), Kamiranzovu Swamp (1950 m) and Kashiru Swamp (2014 m) in Uganda, Rwanda and Burundi respectively and separated from one another by distances of 120–240 km (Fig. 1). Swamp vegetation at Muchoya is dominated by the sedge *Pycreus nigricans* (Steud.) C.B. Clarke with scattered bushes of *Erica kingaensis* Engl. (Morrison, 1968; Taylor, 1990), Kamiranzovu is extensively covered by *Cyperus latifolius* Poir., with a central zone of *Syzygium cordatum* Krauss bordered by *Erica kingaensis* (Deuse, 1966; Bouxin, 1974), and Kashiru supported a *Xyris*/*Sphagnum* community prior to its destruction by peat mining in 1986 (Bonnefille and Riollet, 1988). All sites lie within the lower part of the Montane Forest Belt (Hamilton, 1982). Forest still persists around Muchoya and Kamiranzovu (Echuya and Nyungwe Forests), but has been removed at Kashiru to make way for agriculture.

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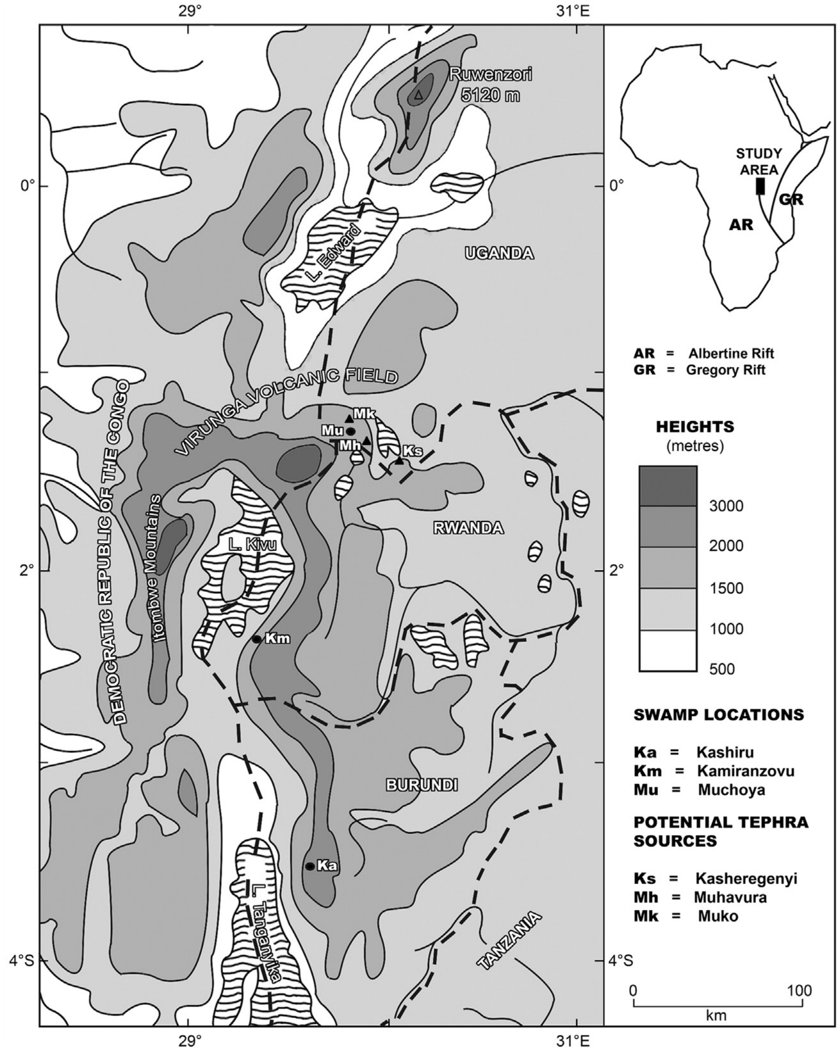

Fig. 1. Locality map. The altitudes and co-ordinates of the three sedimentary sites discussed are: Muchoya Swamp (2260 m; 1°17′S, 29°48′E); Kamiranzovu Swamp (1950 m; 2°40′S, 29°05′E) and Kashiru Swamp (2014 m; 3°28′S, 29°34′E).

2. Sediment sampling and profiles

Sediments were examined at four places at Muchoya Swamp (cores MC1–4) and one each at Kamiranzovu and Kashiru. Sediment sampling was by a Hiller borer at Kamiranzovu and Muchoya and a Russian borer at Kashiru, except at depth at Muchoya where a 20 cm auger was substituted. Sediment sampling and subsequent pollen analysis at Kashiru were by Bonnefille and Riollet (1988) and at the other two sites by one or both of ourselves. In principle, a Russian borer should allow the extraction of sediments less likely to be contaminated with foreign carbon than with the other devices, but it cannot penetrate stiff sediments, for which a Hiller borer is more suitable, or, if very stiff, an auger. Core MC2 at Muchoya, which, at 20.54 m, is one of the longest hand-drilled through Quaternary sediments in Africa, contains very stiff sediment at depth. Great care was taken at Muchoya and Kamiranzovu to avoid contamination of the samples collected for pollen analysis or radiocarbon dating, an ambition generally achieved judging by the conformability of nearly all the radiocarbon dates despite the great ages of some.

The stratigraphy of the sediments in the lower parts of cores MC2 and MC4 at Muchoya and at Kamiranzovu and Kashiru is shown on Fig. 2, together with pollen zones and calibrated radiocarbon dates (given as 95.4% probability ranges; see caption to Table 2 for details of calibration). Identification of the sediment types is as described in the field, augmented by the results of palynological and other laboratory investigations.

Kamiranzovu differs from the other sites in that there is a layer of grey sticky clay (marked L^3 on Fig. 2) above a stratum of organic clay dating to the *Cliffortia* Zone. Its appearance is similar to that of a clay layer below the *Cliffortia* Zone (L^2) and to another (L^1) below the mud that is suspected to be a fossil soil. The pollen spectra of L^3, L^2 and the uppermost part of L^1 are similar, indicating the presence of *Syzygium* swamp forest. It is postulated that the anomalous presence of a second forest zone (Forest Zone 2) contained within L^3, is due to re-deposition of material at the locality of the coring site eroded out of exposures of L^1 and/or L^2 exposed elsewhere on the mire. L^2 might also be redeposited material.

3. Dating

Twenty radiocarbon dates older than 29,000 cal BP are available for the four cores. They are arranged on Table 2 to allow visual estimates of the ages of the transitions between Forest Zone 1 and the *Cliffortia* Zone, being placed in order of depth within each core and grouped according to pollen zone. This is one approach to modelling the radiocarbon data to reveal the possible ages of boundaries between the pollen zones. We are cautious about applying modelling using interpolation to determine the ages of zonal boundaries especially in the lower parts of these

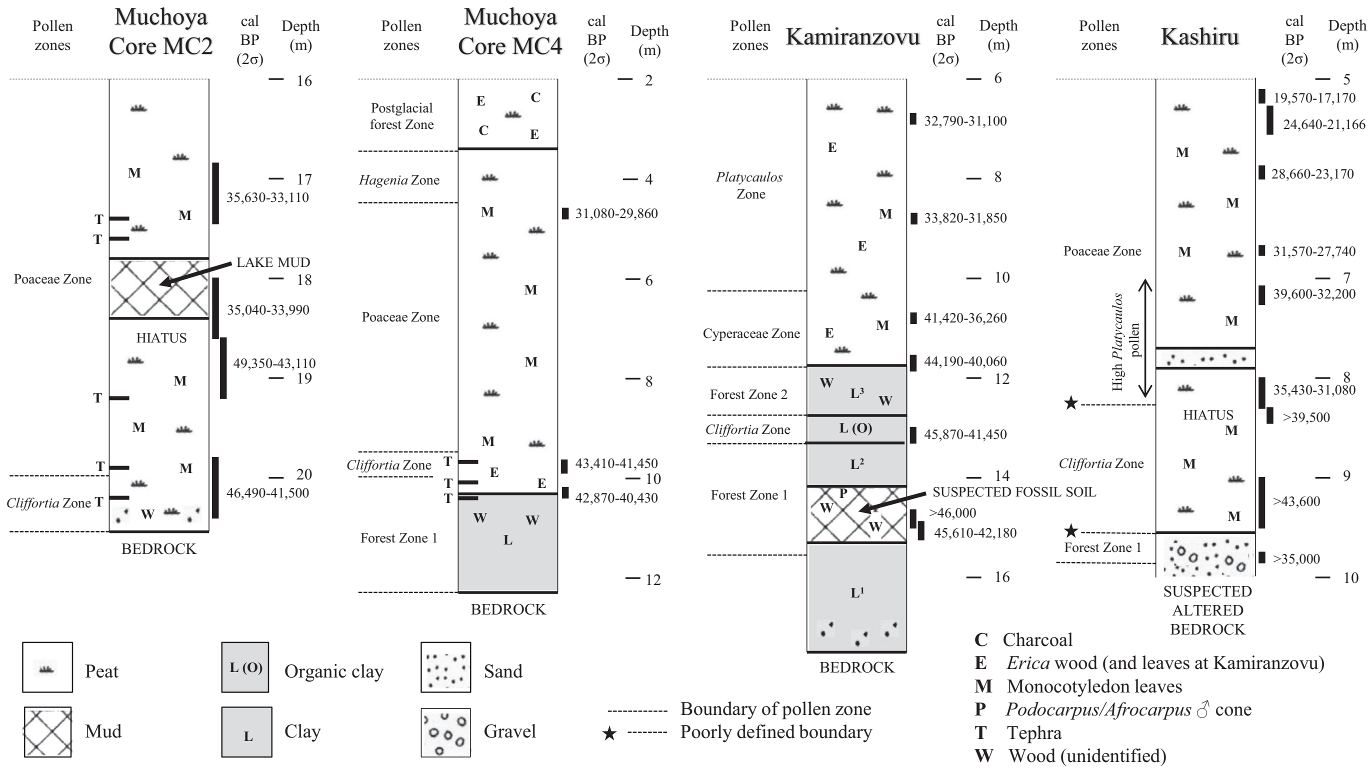

Fig. 2. Stratigraphy of the lower parts of cores through upper Quaternary sediments at Muchoya, Kamiranzovu and Kashiru (Hamilton, 1982; Bonnefille and Riollet, 1988; Taylor, 1990; Bonnefille et al., 1992). Vertical scales vary between cores. Core MC2, the deepest of four cores at Muchoya, is situated at the centre of a transect line across the swamp ~300 m from its effluent. Two other cores (MC1, MC3) lie on either side. Core MC4 is ~2 km up-valley. See Table 2 for details of radiocarbon samples. The *Erica* wood in the peat at Muchoya and Kamiranzovu was identified by its anatomy. The *Erica* leaves at Kamiranzovu match those of *Erica kingaensis* Engl. subsp. *rugegensis* Alm & T.C.E. Fr. (Bridson, pers. comm.), which is the subspecies found on mires (Beentje, 2006). The names given to the pollen zones are chosen to allow easy comparison between the sites. Pollen zones above the *Cliffortia* Zone at Muchoya and Kashiru are named after pollen types thought to have been derived only or predominantly from plants growing on dry land. Pollen thought to have originated from dryland plants is rare at Kamiranzovu and the pollen zones are named after plants thought to have been growing in the wetland or otherwise close to the sample site. The relatively low proportion of pollen originating from greater distances at Kamiranzovu is as expected from studies of modern pollen deposition (Hamilton, 1972; Hamilton and Perrott, 1980), because of its very large size (13 km^2) and virtually circular shape, the locality of the core being near its centre and so relatively distant from sources of dryland pollen. The boundaries between the basal pollen zones at Kashiru are less distinct than those at Muchoya or Kamiranzovu and there was at least one long hiatus in sediment accumulation. The boundary between the *Cliffortia* and Poaceae Zones for Kashiru is drawn on the profile considering the level at which *Platycaulos* (*Restio*) pollen becomes abundant, thought to be about 36,000 cal BP (Bonnefille et al., 1990).

cores, given that cross-comparison of the diagrams and dates shows that rates of sediment accumulation have been very variable and hiatuses have likely occurred. These sediment profiles are similar in these respects to many others that have been studied under mires in eastern Africa (Thompson and Hamilton, 1983; Hamilton and Taylor, 1986).

Taking standard deviations into account and noting the four points below, we assess that 18 of the 20 dates are supportive of the hypothesis that the transition between Forest Zone 1 and the *Cliffortia* Zone was coeval at all sites and occurred at ca. 43,000–40,000 cal BP. Refinement will require further research. The degree of support for this hypothesis is considered remarkable given the great age (towards the limit of radiocarbon dating), uncertainties in dating due to the extensive depth ranges of some of the sediment samples taken for radiocarbon dating and lack of dates for critical horizons (that is, those known with certainty to be just above or below the boundary between Forest Zone 1 and the *Cliffortia* Zone).

The following were taken into account in reaching this dating conclusion:

1. There is one date that is certainly contradictory to the hypothesis of contemporaneity of the Forest Zone 1/*Cliffortia* Zone boundary, that of 49,350–43,110 cal BP (Pta-4195) from Muchoya. This date was given special weight in the original interpretation of the pollen diagrams for this site, leading to the conclusion that both Forest Zone 1 and the *Cliffortia* Zone were older (Taylor, 1990). We offer no explanation for this anomaly.
2. Some of the samples near the base of the cores may contain old carbon from fossil soils. Modern forest soils can give radiocarbon ages dating back to many thousands of years BP (Passenda et al., 2001). Although well above the *Cliffortia* Zone stratigraphically, this could also be true of sample SRR-1617, given that it includes some sediment (clay layer L^3) suspected to be inwashed material dating to earlier than the *Cliffortia* Zone. However, the amount of carbon from this largely inorganic source is likely to be low compared with the contribution from post-*Cliffortia* Zone peat (also included in the sample).
3. The inversion of the ages of the two basal radiocarbon dates at Kamiranzovu, infinite (SRR-1619; >43,040 ^{14}C BP) and 45,610–42,180 cal BP (SRR-1127; 39,838 + 1050/−930 ^{14}C BP), may be related to the use of the two-borehole coring technique used for sediment collection (De Vleeschouwer et al., 2010/11). This was suggested in the original publication describing this core (Hamilton, 1982). The bores may have diverged significantly at great depth.
4. There is some uncertainty about the depths at which the basal two samples for radiocarbon dating were collected at Kashiru (UQ-763, UQ-1456), because contradictory figures are given in the original publication describing the core (Bonnefille and Riollet, 1988). We take those depths repeated in a subsequent article as correct (Bonnefille et al., 1992). The boundaries between the *Cliffortia* Zone and higher and lower pollen zones are less well defined at Kashiru, compared with Muchoya and Kamiranzovu, likely related in part to a long hiatus in sediment accumulation (see caption to Fig. 2).

4. Palynology and inferred palaeo-environments

Pollen diagrams for the three sites have been published elsewhere (Hamilton, 1982; Bonnefille and Riollet, 1988; Taylor, 1990). They extend further back in time than any others so far available for the rift-shoulder highlands (Morrison, 1968; Morrison and Hamilton, 1974; Taylor, 1990; Jolly and Bonnefille, 1991; Bonnefille et al., 1992; Jolly et al., 1994; Bonnefille et al., 1995; Jolly et al., 1997; Marchant et al., 1997). These diagrams, when considered together, show that there was a major climatic transition at about 14,000–11,500 cal BP from a long phase that was relatively cold and often dry to one, still continuing, that is warm and generally comparatively wet. The two phases correlate with the latter part of the last glacial period and the postglacial. The first phase extends back to the beginning of the *Cliffortia* Zone at Muchoya and Kashiru and to the end of Forest Zone 2 at Kamiranzovu (ca. 43–40 ka cal BP).

The latter part of the last glacial period was marked by abundant grasses at all three sites, a scarcity of trees (except sometimes for *Hagenia abyssinica* (Bruce) J.F. Gmel. – a species characteristic of Upper Montane Forest) and the frequent occurrence of shrubs typical of drier types of Ericaceous Belt vegetation (above the Montane Forest Belt) – *Anthospermum* (presumed *Anthospermum usambarense* K. Schum), *Artemisa afra* Jacq. ex Willd., *Cliffortia nitidula* (Engl.) R.E. & T.C.E. Fr. and *Stoebe kilimandscharica* O. Hoffm. Moist Lower Montane Forest replaced these higher altitude vegetation types at about 11,500 cal BP, thereafter persisting until the clearance of much of it for agriculture (Morrison and Hamilton, 1974; Hamilton et al., 1986; Taylor, 1990; Hamilton et al., 2016).

The basal two pollen zones, both present in the pollen diagram for core MC4 at Muchoya, as well as the pollen diagrams for Kamiranzovu and Kashiru, are a lowermost pollen zone containing abundant arboreal pollen (Forest Zone 1) and an upper zone with abundant pollen of *Cliffortia* (*Cliffortia* Zone). Sedimentation at the site of Core MC2 at Muchoya appears to have commenced later. The lowermost pollen zone present in each core is contained within sediment that rests directly on bedrock or consists of material suspected to be fossil soil. Sediment dating to the *Cliffortia* Zone is more organic than that of sediments beneath, being peat at Muchoya and Kashiru.

Several pollen types recorded in Forest Zone 1 at Muchoya and/or Kashiru indicate the presence of Moist Lower Montane Forest on surrounding slopes (Bonnefille and Riollet, 1988; Taylor, 1990). They include *Alchornea*, *Ficalhoa*, *Macaranga*, *Olea* and *Podocarpus*. The climate at Muchoya has been estimated to have been similar to the present (Taylor, 1990), but intermediate between that of the last glacial maximum and the postglacial period at Kashiru (Bonnefille and Riollet, 1988). Much of the arboreal pollen in Forest Zone 1 at Kamiranzovu is Myrtaceae, the pollen spectra being similar to those of surface samples collected from within modern *Syzygium cordatum* swamp forest (Hamilton, 1972). Kamiranzovu is the highest altitude site in the rift-shoulder highlands at which *Syzygium* has been recorded growing on mires today (Table 1), which suggests that temperatures during Forest Zone 1 times were at least as warm as they are now.

An exceptional find at Kamiranzovu was of a male cone of *Podocarpus*/*Afrocarpus* recovered from sediment 5 cm below the top of a layer thought to be a fossil soil (Fig. 2). The plant must have been growing locally. The cone has been identified as probably *Afrocarpus* (*Podocarpus*) *usambarensis* (Pilg.) C.N. Page (Bridson, pers. comm.), a species known from seasonal swamp forest at ~1160 m altitude near Sango Bay on the north-west shore of Lake Victoria (Katende et al., 1995; Lwanga, 1996) and which also grows in drier types of montane forest. *Afrocarpus usambarensis* is not certainly recorded from Kamiranzovu or surrounding Nyungwe Forest today. One of us (AH) has seen a species of *Podocarpus* or *Afrocarpus* growing in the marginal zone where Kamiranzovu Swamp abuts onto forest on dry land, but did not ascertain its precise identification at the time. This may have been *Podocarpus latifolius* (Thunb.) R. Br. ex Mirb., since this has been reported from this marginal zone (Killmann and Fischer, 2005). Elsewhere in Nyungwe Forest, *P. latifolius* is found on upper hillslopes, similar to its pattern of distribution in Bwindi-Impenetrable Forest in Uganda (Hamilton, 1969), further north along the rift-shoulder highlands. It is also found in low altitude swamp forest at Sango Bay, accompanying *A. usambarensis*.

Cliffortia is a genus of 132 species, strongly concentrated in the Cape Floristic Region where 124 species occur, 109 being endemic (Whitehouse and Fellingham, 2007). The only species found in East Africa is *Cliffortia nitidula* (Graham, 1960). A published photograph of a fossil grain of *Cliffortia* from Kamiranzovu is a close match for *C. nitidula*. (Hamilton, 1982). *Cliffortia nitidula* is a light-demanding shrub, sometimes thicket-forming or riparian, typical of drier types of lower Ericaceous Belt vegetation or glades in bamboo forest (Graham, 1960; Coetzee, 1967; Beentje, 1994; Wooller et al., 2003). The distribution of its pollen in surface samples and Quaternary sediments collected from different altitudes on Mt. Kenya (Coetzee, 1967; Wooller et al., 2003) is supportive of the view that its pollen is a good marker for the presence of the lower Ericaceous Belt.

Cliffortia is absent today from the Albertine Rift-margin highlands in Uganda, but does grow at the exceptionally low altitude of 2340 m at Kuwasenkoko Swamp in Rwanda (like Kamiranzovu, in Nyungwe Forest), where it is found at the interface between *Pycreus nigricans* on the swamp and tussock grassland on surrounding slopes (Hamilton, 1982). This low altitude occurrence is clearly related to temperature inversion in the small virtually enclosed valley in which the swamp lies and is taken as further evidence that it can be used as an indicator of temperature conditions similar to those found today in the lower part of the Ericaceous Belt. Hillslopes at 2300–2400 m around Kuwasenkoko display an inverted sequence of vegetation zones, with montane forest with *Ocotea*, *Podocarpus*, *Syzygium* and abundant *Macaranga kilimandscharica* Pax above, *Hagenia* and then tree heather below, and finally tussock grassland on the valley floor (Hamilton, 1982; Killmann and Fischer, 2005). *Cliffortia* at Kuwasenkoko does not occur on the swamp itself, which is consistent with records from elsewhere in eastern Africa showing that it is not a true swamp species. It is likely to have been growing on mineral-rich soils (rather than inorganic peat) during *Cliffortia* Zone times at Muchoya, Kamiranzovu and Kashiru, a habitat then on offer at all judging by the sediment profiles.

Past temperatures are calculated from pollen diagrams in East Africa mainly based on the altitudinal movements of plants. A standard procedure treats plant taxa identified in pollen diagrams as potentially

Table 1
Occurrence of *Syzygium cordatum* and *Erica kingaensis* on mires along the Albertine Rift. Both species grow on oligotropic peat, the latter replacing the former with altitude (Thompson and Hamilton, 1983). The many thousands of years during which wood of *Syzygium* (at Ahakagyezi) and *Erica* (at Kamiranzovu and Muchoya) continued to be incorporated into accumulating peat show that both can be climax species. Both species also occur in other habitats. Their total altitudinal ranges in East Africa are 900–2400 m (*S. cordatum*) and 1600–3500 m (*E. kingaensis*) (Verdcourt, 2001; Beentje, 2006).

Locality	Altitude (m)	*Syzygium cordatum*	*Erica kingaensis*	References
Ahakagyezi Swamp, Uganda	1830	+	−	(Hamilton, 1969)
Kamiranzovu Swamp, Rwanda	1950	+	+	(Deuse, 1966, Bouxin, 1974)
Butongo Swamp, Uganda	2025	−	+	(Morrison and Hamilton, 1974)
Muchoya Swamp, Uganda	2256	−	+	(Taylor, 1990)
Rwenzori swamps, Uganda	≤2750	−	+	(Hamilton, 1969)

Table 2
Radiocarbon dates older than 29,000 cal BP for sediment under Muchoya, Kamiranzovu and Kashiru Swamps (Hamilton, 1982; Bonnefille and Riollet, 1988; Taylor, 1990; Bonnefille et al., 1992). The dates are placed in order of depth within each core and grouped according to pollen zone. Depths and dates for Kashiru follow (Bonnefille et al., 1992). Calibration of these dates and others given in the present paper was by OxCal 4.3 (update of 11 April 2017) (Bronk Ramsey, 2009), using the IntCal13 calibration curve (Reimer et al., 2013). The ^{14}C values for the 'greater than' dates are given in the text.

Pollen zones	Dates and inferred past environments	Relationship of sediment samples used for ^{14}C dating to pollen zones	Laboratory reference number	Locality and core (in brackets)	Depth (m)	Age (^{14}C BP)		Age (cal BP). Ranges are for 95.4% probability
						Age	Standard deviation (±)	
Zones younger than the *Cliffortia* Zone (but see comment on SRR-1617 in column to right).	From the end of the *Cliffortia* Zone to ~29 cal BP or later during the last glacial period. Ericaceae Belt-type vegetation on dryland around the mires, few trees. Cyperaceae common on the mires at all sites. *Erica kingaensis* on the mire at Kamiranzovu. Particularly wet conditions in the three sedimentary basins at ~34,000 cal BP, with lacustrine conditions at Muchoya and a *Platycaulos* (*Restio*)/*Sphagnum* community at Kamiranzovu and Kashiru (Bonnefille et al., 1990). Temperatures lower than now and climate usually drier.	All sediment samples postdate the *Cliffortia* Zone (but SRR-1617 might contain some inwashed old carbon).	UQ-875	Kashiru	6.76–6.85	25,500	1000	31,570–27,740
			SRR-2956	Muchoya (MC4)	4.60–4.90	26,360	300	31,080–29,860
			SRR-1614	Kamiranzovu	6.70–6.90	27,855	+380/−365	32,790–31,100
			SRR-1615	Kamiranzovu	8.70–8.90	28,875	+385/−365	33,820–31,850
			UQ-1246	Kashiru	7.08–7.25	31,000	1500	39,600–32,200
			UQ-1278	Kashiru	8.00–8.30	29,000	1100	35,430–31,080
			Pta-3535	Muchoya (MC2)	16.80–17.40	30,200	640	35,630–33,110
			SRR-2963	Muchoya (MC2)	18.00–18.60	30,550	290	35,040–33,990
			SRR-1616	Kamiranzovu	10.70–10.90	34,270	+1145/−1000	41,420–36,260
			Pta-4195	Muchoya (MC2)	18.60–19.20	42,000	1700	49,350–43,110
			SRR-1617	Kamiranzovu	11.55–11.85	37,630	+1150/−1010	44,190–40,060
Cliffortia Zone.	Beginning sometime within the period ~43,000–40,000 cal BP. *Cliffortia* thicket on mineral-rich substrates near sample sites. Temperatures ~6 °C lower than either now or during Forest Zone 1 times.	Sediment samples include at least one horizon dating to the *Cliffortia* Zone.	UQ-1049	Kashiru	8.30–8.45	> 35,000		>39,500
			UQ-763	Kashiru	9.00–9.50	> 40,000		>43,600
			SRR-2957	Muchoya (MC4)	9.65–9.90	38,200	+670/−620	43,410–41,450
			SRR-1618	Kamiranzovu	13.00–13.30	39,240	+1300/−1120	45,870–41,450
			Pta-3811	Muchoya (MC2)	19.80–20.40	39,500	1400	46,490–41,500
Forest Zone 1.	Extending up to the beginning of the *Cliffortia* Zone. Lower Montane Forest on dryland around Muchoya and Kashiru. *Syzygium* swamp forest at Kamiranzovu. Climate similar to that of today.	All sediment samples date to Forest Zone 1. Some might incorporate old carbon from fossil soils.	SRR-2958	Muchoya (MC4)	10.20–10.40	37,280	+750/−680	42,870–40,430
			SRR-1619	Kamiranzovu	14.65–15.00	> 43,040		>46,000
			UQ-1456	Kashiru	9.75–9.85	> 31,000		>35,000
			SRR-1127	Kamiranzovu	14.90–15.25	39,838	+1050/−930	45,611–42,180

behaving individualistically in relation to past changes in temperature (Hamilton, 1972; Hamilton, 1982). This is in line with floristic studies that show that different species of plants today vary greatly in the lower and upper limits of their altitudinal ranges on the East African mountains (Hamilton, 1975; Hamilton and Perrott, 1980), as well as being in accord with the individualistic behaviour of certain taxa noted in some pollen diagrams (Livingstone, 1967; Hamilton, 1989). Based on such reasoning, the authors responsible for the original papers for Muchoya and Kashiru calculated that the presence of *Cliffortia* in the *Cliffortia* Zone indicates an altitudinal depression of vegetation by ~1000 m compared with today (Bonnefille and Riollet, 1988; Taylor, 1990), which is equivalent to temperature depression by 5.8 ± 0.1 °C assuming the modern lapse rate, or slightly greater if the lapse rate was steeper, as it was later during the last glacial maximum (Loomis et al., 2017). All those responsible for the original interpretations of the pollen diagrams hold that the climate also became drier (Hamilton, 1982; Bonnefille and Riollet, 1988; Taylor, 1990).

The potentially individualistic behaviour of species to changes in temperature and water availability was taken into account in re-assessments of the environmental implications of the first pollen diagrams published for Mt. Kenya (Coetzee, 1967; van Zinderen Bakker and Coetzee, 1972). More recently, research on Mt. Kenya has stressed the potentially individualistic behaviour of plant taxa in relation to changes in other environmental parameters, notable atmospheric CO_2 concentration and burning regime (Olago et al., 1999; Wooller et al., 2003; Street-Perrott et al., 2004, 2007). An abundance of C4 graminoids (grasses and sedges) during the latter part of the last glacial period is attributed to a combination of low atmospheric CO_2 levels and high water stress, the influence of changes in temperature being downplayed. Taking additional factors into consideration, the researchers argue that depression of temperatures during the latter part of the last glacial period may not have been as great as formerly supposed. It is possible that temperature reduction at the boundary between Forest Zone 1 and the *Cliffortia* Zone seen in pollen diagrams for sites along the Albertine Rift may also have been less than earlier calculated, though the conclusion that there was a substantial fall in temperature still stands.

Attention to the possibility of fire influencing vegetation development at Muchoya is highlighted by the presence of three thin layers of tephra associated with the *Cliffortia* Zone, or slightly lower or higher in the sediment columns (Fig. 2). Muchoya is close to volcanic vents with associated lava flows. Other tephra layers occur higher up the sediment sequence, but dwindle in number towards the surface. One past change in vegetation at Muchoya has been attributed to burning, a transition from *Erica* to sedge-dominated vegetation on the swamp at ~1000 BP, probably caused by a high intensity of burning by people (Taylor, 1988). Otherwise, there is no evidence from charcoal or other markers that fire has been a significant influence on vegetation development at Muchoya, though it is suspected that deposition of fresh volcanic ash during the *Cliffortia* Zone may have encouraged the growth of the tree *Cornus volkensii* Harms (Taylor, 1988). No tephra layers were noted in the sediments at Kamiranzovu and Kashiru, neither of which is close to volcanic vents, nor any evidence that fires have influenced the vegetation.

5. Conclusions and comparisons

It is concluded that there was a change in climate in the region of the Albertine Rift at about 43,000–40,000 cal BP, marked by a major reduction in temperature and onset of a drier climate. Depressed temperatures then continued until the transition to a postglacial climate dating to about 14,000–11,500 cal BP. A tectonic event, causing back-tilting of the valley, has been suggested as a possible responsible agent for the creation of the sedimentary basin at Muchoya (Taylor, 1990) and the same could be true also of Kamiranzovu and Kashiru. If so, then a major tectonic event is postulated affecting at least a 240 km-section of the Albertine Rift. Further research is needed to confirm these conclusions, utilising a fuller range of analytical tools than those previously employed.

A similar climatic change to that experienced along the Albertine Rift may have influenced the vegetation of the Eastern Arc Mountains in Tanzania, where pollen evidence suggests significant vegetation changes at ~40,000 cal BP (only approximately dated) (Finch et al., 2009, 2014). A pollen diagram for a site at 2000 m on the Udzungwa Mountains shows an abrupt *Podocarpus* decline and increases in Cyperaceae and Poaceae at about this time, while another, at 2600 m on the Uluguru Mountains, also shows a decline, though less abrupt, in *Podocarpus*, in this case associated with an increase in Ericaceae. These events have similarities to those experienced at the transitions between Forest Zone 1 and the *Cliffortia* Zone at Muchoya, Kamiranzovu and Kashiru. The less abrupt decline in *Podocarpus* pollen at the Uluguru site, compared with that on the Udzungwa Mountains, may be related to its greater proximity to the Indian Ocean. Biogeographical considerations (Lovett, 1993; Fjeldså and Lovett, 1997), plus some palynological evidence (Mumbi et al., 2008; Finch et al., 2014), suggest that the ocean may have moderated the effects on nearby mountains of climatic fluctuations during the Quaternary.

The magnitude of climatic deterioration and the long persistence of a cold climate thereafter have similarities with events in western Eurasia between ca. 40 cal BP and the beginning of the postglacial. In western Eurasia's case, climatic deterioration is believed to have been triggered by a combination of a super-eruption in southern Italy, the Campanian Ignimbrite (CI) eruption, and the beginning of Heinrich Event 4 (HE4), when large armadas of icebergs invaded the North Atlantic, influencing thermohaline patterns and consequently causing extensive modifications to climates. The CI/HE4 combination is believed to have proved a tipping point for a climatic system that was unstable at the time, contributing to the longevity of the cold times that followed (Fedele et al., 2008; Fitzsimmons et al., 2013). The transition from the Middle to Upper Palaeolithic cultural phases and the replacement of Neanderthals by modern humans over much of Europe date to about the time of CI/HE4. There is debate on the level of influence of CI/HE4 over these events (Sepulchre et al., 2007; Fedele et al., 2008; Hoffecker et al., 2008; Hoffecker, 2009; Golovanova et al., 2010; d'Errico and Banks, 2015).

The CI super-eruption has been dated at 40,012 calendar years BP_{GISP2} based on correlation with Greenland ice core tephrostratigraphy (Fedele et al., 2008) and at 39,850 ± 140 or 39,280 ± 110 BP according to $^{40}Ar/^{39}Ar$ measurements on CI (De Vivo et al., 2001; Douka et al., 2010; Giaccio et al., 2017). The beginning of HE4 has been dated to 39,700 BP, based on ^{230}Th dating and $\delta^{18}O$-$\delta^{13}C$ analysis of a stalagmite from a site in central China (Zhou et al., 2014). Our estimated date for abrupt climatic cooling in equatorial Africa of about 43,000–40,000 cal BP is close to these figures, but margins of error are high and more research is required to confirm that they were contemporaneous. More work is also needed to improve the precision of dating of cultural and evolutionary events at about the time of CI/HE4 in western Eurasia. There are anomalies in some radiocarbon dates, potential causes of which are contamination and a peak in cosmogenic nuclide production at about 40,000 cal BP associated with the Laschamp geomagnetic excursion (Lal and Charles, 2007; Fedele et al., 2008; Hoffecker, 2009; Douka et al., 2010; Golovanova et al., 2010; Hajdas et al., 2011; Nowaczyk et al., 2012).

Sediments of upper Quaternary age suitable for detailed studies of vegetational and climatic history are scarce in Africa. The sedimentary basins situated along the high ground on the shoulder of the Albertine Rift constitute a particularly valuable resource for studying the past. They can provide information on climatic baselines and rhythms that give contexts for studies of modern, anthropogenic climate change. Efforts should be made to safeguard this geological heritage, which is currently threatened by transformation for agriculture and destruction through industrial-scale peat-mining (IMCG, 2017).

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