**Distal tephras of the eastern Lake Victoria Basin, Equatorial East Africa:
Correlations, chronology and a context for early modern humans.**

Nick Blegen*

Department of Anthropology

University of Connecticut

Storrs, CT 06269, USA

E-mail: nicholas.blegen@uconn.edu, nick.blegen@gmail.com

*Corresponding author= Nick Blegen +1(847) 436-3854

Christian A. Tryon

Department of Anthropology

Harvard University

Peabody Museum

11 Divinity Ave

Cambridge, MA 02138, USA

E-mail: christiantryon@fas.harvard.edu

J. Tyler Faith

School of Social Science

University of Queensland

Brisbane, QLD 4072, Australia

E-mail: j.fait@uq.edu.au

Daniel J. Peppe

Terrestrial Paleoclimatology Research Group

Department of Geology

Baylor University

Waco, TX 76798, USA

E-mail: daniel_peppe@baylor.edu

Emily J. Beverly

Terrestrial Paleoclimatology Research Group

Department of Geology

Baylor University

Waco, TX 76798, USA

E-mail: Emily_Beverly@baylor.edu

Bo Li

Centre for Archaeological Science

School of Earth & Environmental Sciences

University of Wollongong

Wollongong NSW 2522 Australia

bli@uow.edu.au

Zenobia Jacobs

Centre for Archaeological Science

49 School of Earth & Environmental Sciences
50 University of Wollongong
51 Wollongong NSW 2522 □ Australia
52 zenobia@uow.edu.au
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94 **Abstract**

95 The tephrostratigraphic framework for Pliocene and Early Pleistocene
96 paleoanthropological sites in East Africa has been well established through nearly 50 years
97 of research, but a similarly comprehensive framework is lacking for the Middle and
98 particularly the Late Pleistocene. We provide the first detailed regional record of Late
99 Pleistocene tephra deposits associated with artifacts or fossils from the Lake Victoria
100 basin of western Kenya. Correlations of Late Pleistocene distal tephra deposits from the
101 Wasiriyia beds on Rusinga Island, the Waware beds on Mfangano Island and deposits
102 near Karungu, mainland Kenya, are based on field stratigraphy coupled with 916 electron
103 microprobe analyses of eleven major and minor element oxides from 50 samples. At least
104 eight distinct distal tephra deposits are distinguished, four of which are found at multiple
105 localities spanning >60 km over an approximately north to south transect. Our correlation
106 and characterization of volcaniclastic deposits expand and refine the current stratigraphy
107 of the eastern Lake Victoria basin. This provides the basis for relating fossil- and artifact-
108 bearing sediments and a framework for ongoing geological, archaeological and
109 paleontological studies of Late Pleistocene East Africa, a crucial time period for human
110 evolution and dispersal within and out of Africa.

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113 Keywords: tephrostratigraphy; East Africa; Middle Stone Age; human evolution

1. Introduction

Fossil evidence suggests the earliest members of our species, *Homo sapiens*, first appeared in equatorial East Africa by 195 ka (Brown et al., 2012; McDougall et al., 2005). This area likely served as one point of departure for subsequent Late Pleistocene hominin dispersals across and out of Africa (Rito et al., 2013; Rose et al., 2011; Soares et al. 2012). The archaeological record and environmental context of these early *H. sapiens* populations are essential data for understanding the evolutionary success of our species (e.g., Tryon and Faith, 2013). Continental and regional syntheses of the Pleistocene African archaeological and environmental records are often characterized by mismatches in temporal and spatial scales (reviewed in Blome et al., 2012; Tryon and Faith, 2013). Deep cave sequences in northern and particularly southern Africa have provided finely resolved, rich archaeological and environmental records (e.g., Avery et al., 1997; Clark-Balzan et al., 2012; Deacon, 1979; Garcea, 2010; Henshilwood et al., 2002; Jacobs et al., 2006, 2008; Marean et al., 2000; Marean et al. 2007; Singer and Wymer, 1982; Wadley and Jacobs, 2006). However, deeply stratified cave sequences are largely lacking in East Africa, where the archaeological record consists of generally low-density open-air sites (Tryon and Faith, 2013). Demonstrating stratigraphic equivalence among these open-air sites via the correlation of tephra provides the means to assess landscape-scale spatial variation in past environments and human behaviors.

East Africa has the potential to demonstrate the equivalence among sites via tephrostratigraphy, the geochemical and lithostratigraphic correlation of tephra as widespread markers in the geological record (Brown and Nash, 2014; Lowe, 2011).

Rifting along the East African Rift System (EARS; Chorowicz, 2005) provides the mechanisms for volcanic eruptions, rapid sedimentation and burial of archaeological and paleontological sites, as well as their subsequent exposure through continued faulting. Although there is a well-established Pliocene and Early Pleistocene tephrostratigraphic framework for paleoanthropological sites in Kenya, Ethiopia, Tanzania and Uganda that is the outcome of nearly 50 years of research (e.g., Brown et al., 1992, 2006; Feibel, 1999; Hay, 1976; McHenry et al., 2008; Pickford et al., 1991; Woldegabriel et al., 1999, 2005, 2013), comparatively few data are available for these areas during the portions of the Middle and Late Pleistocene that saw the origin and dispersal of *H. sapiens* (for published exceptions, see Brown et al., 2012; Morgan and Renne, 2008; Sahle et al., 2014; Tryon and McBrearty, 2002, 2006; Tryon et al., 2008, 2010).

We address this problem by focusing on archaeological and paleontological sites associated with tephra deposits in and around the eastern Lake Victoria basin, and develop a Late Pleistocene tephrostratigraphic and chronometric framework for the region. At 66,400 km², Lake Victoria is the largest lake in Africa by surface area (Adams, 1996). The habitats surrounding this lake have undergone substantial climate-driven changes throughout the Quaternary (Bootsma and Hecky, 2003; Nicholson, 1998), likely with profound impacts on human and other animal communities (e.g., Faith et al., 2011, in press; Tryon et al., 2010, 2012). However, until recently, an understanding of environmental variation prior to the Last Glacial Maximum has been poorly constrained, and the nature of spatial variation in environments and human behavior obscured.

We present the results of 916 electron microprobe analyses to geochemically characterize

and correlate 50 distal tephra deposits from 32 measured sections across Rusinga Island, Mfangano Island, and Karungu on the Kenyan mainland (Fig. 1 a,b), spanning a roughly north-south oriented transect over 60 km in the eastern Lake Victoria basin (eLVB). Four tuffs: the Wakondo Tuff, the Nyamita Tuff, the Nyamsingula Tuff, and the Bimodal Trachyphonolitic Tuff are sufficiently distinct and widespread lithostratigraphic markers for correlation within and between discontinuous outcrops at distantly located paleontological and archaeological localities. Optically stimulated luminescence (OSL), Uranium-Thorium disequilibrium (U-Th) and AMS ^{14}C dates constrain the depositional history and ages of these tuffs to >33 to ~100 ka. This stratigraphic sequence of tuffs, radiometric dates, and intercalated fossil- and artifact-bearing sediments provides the fundamental framework to assess paleoecological and archaeological variation across time and space in the eastern portion of the Lake Victoria basin.

2. Pleistocene distal tephra deposits, fossils, and artifacts in the eastern Lake Victoria basin

The Lake Victoria basin formed in the depression between the eastern and western branches of the EARS, probably within the last few million years (reviewed in Danley et al. 2012). The northeastern part of the Lake Victoria Basin (Fig. 1c) is unlikely to have been volcanically active since the cessation of rifting and volcanism associated with the failed Nyanza Rift in the Early Miocene (e.g., Peppe et al., 2009; Van Couvering, 1972). During the Pleistocene, the eLVB formed a repository for sediments, including volcaniclastic deposits from eruptions originating from sources outside of the basin. Tephra input appears to be from multiple sources of the central and southern Kenyan Rift

186 in the eastern branch of the EARS (Fig. 1b), demonstrated by tephra deposits from
187 Kenyan and Tanzanian volcanoes mapped in areas as far west as $\sim 35^{\circ}10'E$ (see Fig. 1b;
188 Dawson, 2008; Peters et al., 2008; Tryon et al., 2010; Williams, 1991). Pleistocene
189 tephra in the eLVB west of $35^{\circ}10'E$ have been previously reported from Rusinga Island
190 (Tryon et al., 2010; Garret et al., in press; Van Plantinga, 2011) and from sediment cores
191 near Buvuma Island (Kendall, 1969: 139) within Lake Victoria, but are poorly
192 documented due to a focus on economic geology or igneous and metamorphic suites in
193 the region (e.g., Le Bas, 1977).

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195 Localities with Pleistocene tephra, fossils and artifacts attributed to the Early Stone Age
196 (ESA), Middle Stone Age (MSA), and Later Stone Age (LSA) archaeological
197 technocomplexes are known from the eLVB in Kenya as discussed below (Tryon et al.,
198 2010, 2012, 2014; Faith et al. in press), as well as from Loiyangalani (HcJd-1) in the ash-
199 rich Serengeti Plain of the eLVB in Tanzania (Fig. 1b, Anderson and Talbot, 1965; Bower
200 et al., 1981; 1985; Pickering, 1959; Thompson, 2005). A number of these western
201 Kenyan sites occur ~ 80 -100 km east of Lake Victoria's Winam Gulf, and are associated
202 with at least two widespread marker tuffs considered useful for local field correlation.
203 Pickford (1982; 1984) termed these the "Nyando Ash" or "Nyando Ashes" (Fig. 1). From
204 the area of mapped exposures of the "Nyando Ashes," McBrearty (1981) excavated lithic
205 artifacts and fossils from within reworked Pleistocene tephra at Songhor near the head of
206 the Nyando River (Fig. 1b,c). McBrearty (1991; 1992) also described a sequence of
207 twelve tuffaceous deposits at the site of Simbi in an area mapped as Nyando Ashes
208 (Fig. 1b,c) and reported a preliminary $^{40}\text{Ar}/^{39}\text{Ar}$ age range of ~ 50 -200 ka (McBrearty,
209 1992). These preliminary dates appear to confirm the Pleistocene age of the Nyando

Ashes, but the number of tuffaceous deposits documented at Songhor, Simbi and Rusinga (McBrearty, 1991, 1992; Tryon et al., 2010; Garret et al., in press; Van Plantinga, 2011) indicates that there are more than the two tephra deposits originally suggested by Pickford (1982, 1984).

Here we couple the first geochemical investigation of the “Nyando Ashes” with geological, archeological, and paleontological data developed during our field program investigating Pleistocene tephra, fossils, and artifacts along the margins of Lake Victoria on Rusinga Island, Mfangano Island and Karungu on the Kenyan mainland (Beverly et al., in press; Garrett et al., in press; Tryon et al., 2010, 2014, 2014; Van Plantinga, 2011).

3. The Wasiriya beds of Rusinga Island, the Waware beds of Mfangano Island and the Pleistocene exposures of Karungu

3.1 The Wasiriya beds

The Wasiriya beds are exposed over an area of approximately 10 km² on the hill slopes around Rusinga Island (Fig. 2, Tryon et al., 2010). These sediments were informally named by Pickford (1984, 1986) based on previous mapping and descriptions (Kent, 1942; Van Couvering, 1972). The first measured sections, sedimentary lithological descriptions and geochemical characterizations and correlation of tephras from the Wakondo and Nyamita localities on Rusinga Island were reported by Tryon et al. (2010). These are shown in Fig. 2, supplemented by new data from the Nyamsingula locality.

235 The Wasiriya beds are exposed in sections that are >10 m at their thickest points, and are
 236 comprised of three primary recognized lithologies: 1) poorly sorted coarse sand and
 237 gravel channels cemented by carbonate representing episodic channel erosion and
 238 deposition, 2) fine grained mudstone, siltstone, and silty sandstones preserving evidence
 239 of incipient soil development indicating a slightly more stable landscape, and 3) tephra
 240 that has undergone varying amounts of reworking and incipient pedogenesis (Tryon et al.,
 241 2010; 2012). AMS ^{14}C dates of gastropod shells primarily from tuffaceous sediments at
 242 the Nyamita 2 and Nyamita 3 localities (Tryon et al., 2010) indicate a minimum age of 33
 243 ka for these and underlying deposits (Tryon et al., 2010; 2012). These dated snails
 244 (*Limicolaria cf. martensiana*) only occur in sediments close to or at the modern surface,
 245 and are found in different types of sediments at the same elevation and position relative
 246 to the modern soil surface. These specimens also primarily occur in life position
 247 suggesting they apparently died during aestivation. Based on these observations, we
 248 interpret that the snails burrowed into the Wasiriya beds following deposition of the
 249 sediment, but prior to lithification, and thus they provide a minimum age for the deposits.
 250 U-series dates of 94.0 ± 3.3 ka and 111.4 ± 4.2 ka on tufa at the base of the Wasiriya beds
 251 sequence exposed at Nyamita (Fig. 2) provide a maximum age for the overlying
 252 sediments (Beverly et al., in press). Stone artifacts from the Wasiriya beds include MSA
 253 Levallois cores and Levallois points as well as bifacial and unifacial trimmed points
 254 (Tryon et al., 2010). Fauna are abundant and include both extinct and extant taxa (Faith et
 255 al., 2011; Pickford and Thomas, 1984; Tryon et al., 2010). Water-dependent taxa are
 256 present (e.g., *Hippopotamus*), but the majority of specimens indicate open, semi-arid

grasslands distinct from the evergreen bushlands, woodlands, and forests historically found in the region (Garrett et al., in press; Tryon et al., 2010; 2014).

3.2 The Waware beds

The Waware beds of Mfangano Island, Lake Victoria, Kenya are relatively poorly exposed over an area of $\sim 7 \text{ km}^2$ on the northeastern periphery of the island (Fig. 2; Tryon et al., 2012). Pickford (1984; 1986) informally named the Waware beds revising previous work (Whitworth, 1961). These deposits, which are all $< 5 \text{ m}$ thick, preserve fluvial sediments with incipient soil development and reworked tuffaceous deposits that unconformably overlie Miocene sediments (Tryon et al., 2012). The fossil and artifact bearing portions of the Waware beds deposits are comprised of fine-grained sandy mudstone and siltstone beds with evidence for varying degrees of pedogenesis interbedded with occasional coarser grained sandstone and conglomerate channel deposits (Tryon et al., 2012).

Based on perceived similarity of Lake Victoria's base level at the times these various beds were deposited, Pickford (1984, 105) inferred that the Waware beds on Mfangano, the Wasiriya beds on Rusinga, and the Apoko Formation of the Homa Peninsula were deposited during the same time period in the Late Pleistocene. The only radiometric ages for the Pleistocene Waware beds on Mfangano Island are AMS ^{14}C dates of 35-42 ka on gastropod shells from the Kakrigu locality (Fig. 2, Tryon et al., 2012). As is the case in the Wasiriya beds on Rusinga Island, the snails (*Limicolaria cf. martensiana*) postdate deposition of the Waware beds, and therefore provide minimum age constraints. Based on

the similar radiocarbon ages from the snails and that the lithofacies of the Waware and Wasiriya beds are identical, we have also suggested that the Waware and Wasiriya beds are most likely contemporaneous (e.g. Tryon et al., 2012; Garrett et al., in press). The archaeology of Mfangano Island as described from surface collected stone artifacts also consist of Levallois technology and bifacial points (Tryon et al., 2012). The fauna are similar to those from Rusinga Island and also indicate an open and arid environment relative to the present (Garrett et al., in press; Tryon et al., 2012).

3.3 Karungu

The Pleistocene beds of Karungu, Kenya, crop out around the town of Sorion the Kenyan mainland (Fig. 3). These beds are discontinuously exposed over an area of $\sim 40\text{km}^2$ and are up to 10.5 m in thickness, overlying eroded topography of Miocene bedrock (Pickford, 1984). The Pleistocene deposits are best exposed at the localities of Kisaaka, Aringo, Aoch Nyasaya and Obware (Figs. 4, 5, 6; Faith et al., 2014a,b), with the most extensive and thickest exposures at Kisaaka (Figs. 3, 4) (Faith et al., in press; Beverly et al., in press). The deposits at Karungu are comprised of fine grained siltstone and mudstone beds that have been pedogenically modified into paleo-Vertisols and paleo-Inceptisols, conglomeratic beds that represent fluvial channels, variably reworked tephra, and tufas deposited by local springs (Faith et al., in press, Beverly et al., in press). On the basis of field characteristics of two widespread tuffs at Karungu, Pickford (1984) proposed correlations among exposures at Karungu, and between Karungu and other western Kenyan Pleistocene localities where the “Nyando Ashes” were also present.

Like the Wasiriya beds and Waware beds described above, all *in situ* and most surface collected stone artifacts documented during fieldwork at Karungu from 2010-2013 are characteristically MSA, including Levallois cores and bifacially worked MSA points. The fauna from Karungu resembles that of the Wasiriya and Waware beds in displaying both extinct and extant taxa, the majority of which indicate an open and semi-arid grassland environment (Faith et al., 2014, in press).

4. Tephra Correlation Materials and Methods

4.1 Materials

All 50 tuff samples analyzed for this study were collected from or can be stratigraphically linked to a series of 32 sections <0.50 m to >10 m thick measured from Pleistocene outcrops on Rusinga Island, Mfangano Island and Karungu between 2009 and 2013. Geographic locations, lithologies, and the location of archaeological and paleontological sites are shown in figures 2-6 and 8 with geographic coordinates for each stratigraphic section provided in Table 2. Whenever possible, tuffs were sampled from sections with multiple tephra deposits exposed in stratigraphic succession. Field correlations were made by walking exposures and by using a Jacob's staff and Abney level to establish the stratigraphic equivalence between exposed tuffs. Both field and laboratory methods of correlation are necessary as exposures are discontinuous and tephra deposits in the eLVB vary widely in their thickness, amount of subsequent soil development, and amount and/or size of natural glass.

4.2 Methods

329 All samples were examined in hand specimen, with low power (10x) magnification in the
330 field, and in thin section from selected specimens using a petrographic microscope at 40-
331 100x magnifications. However, like the vast majority of tephra deposits in East Africa
332 (Brown and McDougall, 2011), the lithological characteristics of the tuffs in outcrop and
333 under magnification are generic and insufficient for correlation due to aeolian
334 fractionation (density-driven separation of the vitric, crystal and lithic phases with
335 increased distance from the source) and varied syn- and post-depositional environments.
336 Although crystal composition can be useful in some settings where glass is not preserved
337 (e.g., McHenry, 2012; McHenry et al., 2008; Smith et al., 2011), we base our correlations
338 on chemical analysis of volcanic glass shards, characterized by electron probe
339 microanalysis of eleven major element oxide proportions (Brown and Nash, 2014). Glass
340 composition provides the most diagnostic ‘fingerprint’ for correlation purposes (Lowe,
341 2011). Correlation identifies deposits that derive from the same eruption, but because
342 tephra can be reworked during and following initial sedimentation (see Orton, 1996 for
343 an extensive review), the presence of the same tephra in multiple outcrops does not
344 necessarily define an isochron or time-plane. Following the terminology of Feibel et al.
345 (1989), all deposits of correlated tephra will share the same eruptive age, but the
346 depositional age will vary according to local conditions. Ideally, dates from multiple
347 outcrops would be used to assess local variance in depositional age, but this is not always
348 feasible. We thus assume only general age equivalence for correlated deposits. However,
349 in some cases at Karungu, Rusinga, and Mfangano additional geological evidence, such as
350 pristine glass shards and evidence that the tephra are airfall deposits (e.g., tephra
351 blanketing and uniformly filling paleotopography) indicates that there has been little to no

reworking of some the tuffs, suggesting that depositional ages likely approximate eruptive ages. Importantly, at Karungu, Rusinga, and Mfangano, we document a stratigraphic sequence comprised of chemically distinct and correlated tuffs is repeated at several localities. This sequence of correlative tephra thus serves as a relative dating tool for interpreting the age relationships of interbedded sediments and fossil- and artifact-bearing sites in the eLVB.

4.3 Preparation

All preparation protocols were adapted from the University of Utah Electron Microprobe lab recommendations (see Brown and Fuller, 2008; Nash, 1992). Bulk samples of tuff (10-30 g) were prepared by disaggregation with pestle and mortar and sieved through 250 and 125 μm mesh screens, retaining the fraction between. Samples were then washed repeatedly with deionized water and the suspended clay fraction was decanted until the effluent was clear. Cleaned tephra was then treated with 10% nitric acid in sonic bath for five minutes to remove carbonates. Tephra samples were subsequently treated for five minutes with 5% hydrofluoric acid in a sonic bath to remove metal salts and clays potentially adhering to the surface of the glass shards. Samples were then rewashed in deionized water until the effluent was clear, and dried in an oven at 90°C for at least six hours or until all visible moisture was removed. Dried samples were magnetically separated on a Franz isodynamic magnetic separator in two successive runs, the first at low (0.1-0.3) amperage to separate the strongly magnetic mineral components such as olivine, augite and opaque minerals, and the second run at higher amperage (~0.9-1.0) in order to separate weakly magnetic natural glass from nonmagnetic feldspars and quartz. Glass separates were mounted in twelve-well epoxy grain mounts at the University of

Utah. Standard mount sizes are 1" (25mm) round mounts with maximum height of 1". The University of Utah electron microprobe lab provided carbon coating of samples with a Denton Benchtop Turbo IV high vacuum evaporator. Each mount contained an MM3 standard obsidian (Brown and Fuller, 2008) so that the samples and standard have the identical thickness of carbon coating. Samples described in Tryon et al. (2010) and Van Plantinga (2011) were previously analyzed in the microprobe as resin-impregnated polished thin sections prepared by Spectrum Petrographics, Inc. To reduce inter-analysis variation resulting from the use of different instrumentation and analytical protocols (cf. Kuehn et al., 2011) that may confound correlation efforts, the current dataset includes new preparation and analysis of all samples from Rusinga Island previously analyzed by Tryon et al. (2010), and sample AV1006T5A from Van Plantinga's (2011) study of the Nyamita Valley (Rusinga Island). New and published results show good correspondence particularly for elements other than those known to be highly mobile (e.g., SiO₂, Na₂O, K₂O) and poorly suited for correlation.

4.4 Analysis

The relations among the vitric, crystal, and lithic phases of the tephra deposits were examined in thin section using plane and polarized light, backscattered electron imagery, and energy dispersive electron probe microanalyses (EPMA). Geochemical characterization of the vitric (glass) phase for thin sections and grain mounts via EPMA used a Cameca SX-50 in the Department of Geology and Geophysics at the University of Utah, USA. Analyses were conducted using PC1, TAP, PET and LiF crystals on four wavelength-dispersive spectrometers, with an accelerating voltage of 15 keV, a beam current of 25 nA, and a spot size of 10 µm. The analytical routine for glass included Si,

Ti, Zr, Al, Fe, Mn, Mg, Ca, Na, K, O, F, and Cl. A natural obsidian standard (MM3) was used for calibration of O-K α , Si-K α , Al-K α , K-K α . Mineral standards include fluorite (F-K α), tugtupite (Cl-K α), albite (Na-K α), diopside (Ca-K α , Mg-K α), hematite (Fe-K α), rutile (Ti-K α), rhodonite (Mn-K α), and cubic zirconia (Zr-L α). Rounds of three standard analyses bracketed rounds of four sample unknowns where 15-20 shots were taken per sample (Nash, 1992). Accidental mineral analyses of feldspars or quartz or analyses with aberrantly low totals (< 90%) were excluded from this study. Oxygen was measured directly allowing for an estimate of the water contents of the shards. This provides a measure of the quality of the analysis (Nash, 1992). Na was measured first on the TAP crystal with an analysis time of four seconds on the analytical peak and two seconds on background on either side of the peak, in order to minimize Na loss under the electron beam. On-peak and background measurement times are as follows (Pk/Bg sec): Si (15/15), Ti (25/25), Zr (37/22), Al (15/15), Fe (25/25), Mn (25/25), Mg (40/40), Ca (20/16), Na (4/4), K (20/16), O (20/20), F (20/20), Cl (20/20). Concentrations are calculated using the PAP matrix correction procedure of Pouchou and Pichoir (1991). Correction for “excess” F by interference of the Fe L α peak with F K α peak was accomplished by measuring a F-free Fe-bearing standard (hematite) to yield a correction factor of 0.031. Background intensities are measured on both sides of the analytical peak for all elements but F on the PC1 crystal, where off-peak background is measured to one side, and on-peak background intensity is interpolated using the estimated slope of the continuum (Pouchou, & Pichoir, 1991).

By choosing analytical conditions identical to those widely used by the Department of Geology and Geophysics at the University of Utah, we are able to directly integrate our

data from the eLVB to a large body of published data on extra-basinal tephra that may be potential correlates (e.g., Brown and Fuller, 2008; Brown et al., 2012, 2013). The selected beam size and current can cause underestimates of volatile element abundance (especially Na) and over-representation of Si, leading to higher than expected totals (cf. Hayward, 2012; Hunt and Hill, 2001; Morgan and London, 1996), and it is for these reasons that we use the restricted element list defined below for our correlations. However, inter-laboratory comparisons confirm that the equipment and protocols used by the Utah laboratory (lab 5 in Kuehn et al., 2011) work exceptionally well for tephras of a wide range of compositions.

4.5 Interpretation

Correlation of two or more tephra deposits is best viewed as a hypothesis with different methods of distinguishing tephras providing independent tests of any hypothesized correlation (Feibel, 1999). Failure to distinguish tephras from different samples by means of stratigraphy, lithology, petrography and element oxide compositions measured with an electron microprobe constitutes robust evidence for correlation (Tryon et al., 2008; 2010). Reported major element oxides are not normalized because element oxide totals including estimated water content were high and exploratory data analysis using normalization did not alter interpretation. However, samples plotted on the total alkali-silica (TAS) diagram (Fig. 7) necessarily have totals normalized to 100% for comparison with whole-rock samples (LeBas et al., 1986).

Our samples include both fresh vitric tephra deposits, as well as those subsequently reworked by fluvial processes or overprinted by pedogenesis. We define fresh vitric tephra as poorly consolidated, well-sorted ash-sized (≤ 2 mm) vitric ashes following the terminology of Schmid (1981: 42). We indicate where tephra of this lithology were sampled in Figs. 2 and 4. The remaining samples of tuffs are more lithified and show incipient pedogenesis or other evidence for bioturbation. The glass shards in these samples are set in a predominantly silt to fine-sand groundmass, and grain boundaries on the glass shards are sharp, indicating little mechanical abrasion through grain to grain collisions through reworking (Tryon et al., 2010). Lithic and crystal phases from the eruption cannot always be reliably distinguished from those found in detrital sediments, and thus our correlations rely on chemical composition of the glass component for all samples.

In the majority of samples, all analyzed glass shards clustered around a discrete mean and represent a unimodal glass composition (Table 1; Fig 9), further indicating minimal reworking even in those ash beds visibly altered by fluvial or pedogenic processes during or after initial deposition. However, some samples displayed bimodal compositions. Bimodal compositions within a single sample were separated into 'a' and 'b' compositions and treated as potentially different tephra for analysis (Fig. 9). Identifying the consistent presence of a bimodal composition is an important step in distinguishing tephra deposits that contain two modes of glass as a product of magmatic processes during eruptions (e.g., due to a differentiated magma chamber or sampling host rock during magma ascent), and therefore represent the same eruptive event, from those that contain two modes as a product of post-depositional mixing. Bivariate plots of Cl versus

TiO₂ visually display the discrete modes of the tuffs discussed in this study (Fig. 9). We chose this combination because it most clearly displays similarities and differences within and between all correlative groups of tuffs on a single plot (Fig. 9). Both TiO₂ and Cl are immobile elements that are unaffected by hydration and analytical variations between samples.

Postdepositional hydration, ion exchange and migration of the alkalis in analysis are known to affect silica (Si), sodium (Na), potassium (K) and possibly fluorine (F) content (Cerling et al., 1985, Hunt & Hill, 2001). These diagenetic and analytical conditions that selectively affect measurement and calculation of SiO₂, Na₂O, and K₂O have prompted us to follow Brown et al., (2012) in excluding these element oxides for correlation purposes. We use a restricted list of seven element oxides, TiO₂, Al₂O₃, FeO, MnO, MgO, CaO, and Cl in computation of similarity coefficients and other statistical analyses. We depart slightly from Brown et al., (2012) by including Al₂O₃. This element oxide is important in distinguishing discrete chemical modes within samples attributed to a widespread bimodal deposit (the BTPT, described below).

All correlations are supported by similarity coefficients (SCs) to quantify similarity between means of glass analyses from samples after which a tephra is named, the ‘type sample’, and the mean value of all other modes in our dataset (Table 2, Brown et al., 2012; Tryon et al., 2008). For any two-tephra comparisons, SCs are the mean of the ratios obtained by dividing pairs of sample means (with the larger value of the two samples always the denominator such that the ratio is always ≤ 1) element by element as defined in Borchardt et al. (1972: 302). In this study we have restricted SC analysis to the seven

element oxides noted above (see Brown et al., 2012). Resulting SCs range from 0 (complete dissimilarity) to 1 (perfect similarity).

Previous studies have proposed arbitrary cutoffs for interpreting SCs in terms of potential correlation. For example, Kuehn and Foit (2006) propose a value of ≥ 0.95 for definitive correlation, whereas Froggatt (1992) recognizes that values ≥ 0.92 are typically accepted for correlations. In this study, we implement randomization procedures to develop empirically informed SC cutoffs for accepting or rejecting potential correlations. For each of the tephra type or representative samples, we use the mean and standard deviation of each element oxide to generate 5,000 random normally-distributed samples using the R statistical package (R Development Core Team, 2014); this effectively represents 5,000 replicates of the type tephra. We then calculate SCs between each of the 5,000 replicates and the type sample, which is used to generate a frequency distribution of expected SC values when comparing two samples of the same tuff. From this distribution, we determine the lower SC limit that encompasses the upper 95% of observations. We use this value as the cutoff for rejecting potential correlations. For example, an SC value between an unknown tuff and a type sample that falls below this cutoff is excluded for consideration as a potential correlate. To increase the stringency of our protocol, we also require that the seven element oxides of the unknown tuff considered in our analysis overlap within two standard deviations of the mean of the type sample. This is because an unknown sample that is very similar in composition for most element oxides (e.g., 6 of 7) to a type sample will record a relatively high SC value, even if one oxide is distinct and outside the range of expected values. The SCs included in this analysis were used as a data exploration and confirmation technique. All correlations were investigated in more

detail utilizing the known stratigraphy of a site and visual inspection of the tephra datasets.

5. Radiometric Dating

There are a number of available methods that focus on the vitric or crystal phases of a tephra to determine its eruption age (Feibel et al., 1989) including fission track, thermoluminescence, and $^{40}\text{Ar}/^{39}\text{Ar}$ methods; other approaches such as U-Pb dating of zircons more accurately dates crystal formation rather than eruption (e.g., Simon et al., 2008). We have not been able to apply any of these methods to directly estimate the eruption ages of any of the eLVB tephra deposits because of iron-oxide mineral inclusions in the glass shards and because datable minerals are either too fine-grained or sparse to be dated.

The alternative approach used here is to determine the depositional age of the tephra (Feibel et al., 1989). Differences in the time between eruption and initial deposition (sedimentation) of fall-out deposits can range from minutes to hours for areas proximal to the source volcano, to several years for finer particles that enter the stratosphere. Once deposited, tephra can be remobilized and reworked through normal sedimentary processes, and thus the timing of re-deposition may differ substantially from the initial depositional age.

We use two methods to estimate the depositional age of the eLVB tuffs. The first, already mentioned, is the direct AMS ^{14}C dating of gastropod shells found in life position within tuffs from Rusinga Island and Mfangano Island. As the snails burrowed into the previous

deposited sediments, they post-date deposition, but apparently pre-date lithification, providing a minimum age for the deposits. The second method was to utilize optically stimulated luminescence dating to determine sediment burial ages.

5.1 Optical dating

We used optical dating of sediments to constrain the age of tephra deposition. All dates derive from localities on Rusinga Island. We collected two sediment samples (RUP-1 and RUP-2) respectively above and below the type sample of the Nyamita Tuff at section Nyamita 2 (Figs 2, 10; Li et al., 2015). As discussed in detail below, textural, microscopic, and geochemical data strongly suggest that this deposit underwent little to no reworking following deposition, and thus depositional age likely approximates eruptive age. At Wakondo we collected three samples (RUP-3, RUP-4 and RUP-5) from the same sedimentary unit in a channel complex ~1 m above the Wakondo Tuff. The age of the channel complex provides a minimum age for the deposition of the Wakondo Tuff. For all samples, we extracted 180-212 μm in diameter potassium-rich (K) feldspar grains, using standard procedures, for dating; no quartz grains were present in the sediment samples. We measured individual grains of K-feldspar from each of the samples for equivalent dose (D_e) determination, using a two-step post-IR IRSL measurement procedure (Thomsen et al., 2008), in which a prior-IR IRSL stimulation at 200 °C (Li and Li, 2012) and a post-IR IRSL stimulation at 275 °C were adopted, to overcome possible age underestimation caused by anomalous fading (Huntley and Lamothe, 2001; Wintle, 1973). The dose rates were estimated using a combination of laboratory-based beta counting, field-based gamma spectrometry measurements, together with calculations of the cosmic ray and internal beta dose rates. The applicability of the pIRIR method for the

samples in this study and the reliability of the measurements were determined using a suite of different tests. A description of the method and D_e and dose rate measurement procedures and the test results are presented in detail in Supplementary Information and in Li et al. (2015).

6.Results

6.1 Tephra Correlation

Element oxide wt. % abundances, and comparisons using SCs indicate the presence of eight distinct distal tephra deposits of nine chemical compositions (Fig. 9, Table 1, 3, 4). Seven of these tephra deposits occur across Rusinga Island, Mfangano Island, and Karungu, four of which are sufficiently widespread to merit names and type or representative localities. These four units in stratigraphic order from the base upwards are the Wakondo Tuff, the Nyamita Tuff, the Nyamsingula Tuff, and the Bimodal Trachyphonolitic Tuff (BTPT). The first three of these deposits include fresh vitric tephra and are named on the basis of a geographic type locality following the North American Stratigraphic code (North American Commission on Stratigraphic Nomenclature, 2005). No such deposits of the BTPT have been found in the eLVB, and we thus provide a provisional name based on its characteristic bimodal chemical composition. Figure 8 shows these deposits in stratigraphic order along with the three unique tuffs from the eLVB: two compositionally similar trachytes from Rusinga Island's Nyamita Valley, and a single rhyolite from the Kisaaka locality at Karungu. The eighth distinct tuff, from Songhor (Figs 1b, 1c), is outside the area of the eLVB that is the

primary focus of this study. Thus this tuff is not shown in Figure 8, but is important in that it suggests a still untapped potential for tephra correlation in and around the eLVB.

6.1.1 The Wakondo Tuff

The Wakondo Tuff is named after the Wakondo locality on Rusinga Island where it was first recognized by Tryon et al. (2010). Because of its fresh lithology, abundant glass and documented stratigraphic position at Wakondo (Fig. 2; Tryon et al. 2010: 5), sample CAT09-05 serves as the type sample of this tephra (Fig. 10a,b).

6.1.1.1 Composition of the Wakondo Tuff

The type sample (CAT09-05) is a ~20-cm-thick, massively bedded, weakly consolidated, grey-green fresh, vitric ash composed of microscopic pumices and pumice fragments (50-200 μm) and sinuous glass shards generally $< 5\mu\text{m}$ to $\sim 100\mu\text{m}$ with oval and linearly stretched vesicles. At the type section, the Wakondo Tuff is interbedded within ~4m of siltstone (Fig. 2, Tryon et al., 2010). The Wakondo Tuff is a phonolite (Fig. 7; Tryon et al., 2010, Van Plantinga, 2011). All samples attributed to it are unimodal (Fig. 9; Table 1). There is minimal evidence for reworking of the Wakondo Tuff at its type locality.

6.1.1.2 Similarity coefficients of the Wakondo Tuff

SC values calculated between CAT09-05 and the randomized replicates of this sample produced an average SC value of 0.95 and a lower 95% confidence limit of 0.93 (Table

2). The seven samples correlated to the Wakondo Tuff have a SC of 0.95 or higher when compared to the type sample CAT09-05 (Table 3). All other tephra samples have SCs of 0.89 or lower when compared with samples of the Wakondo Tuff (Table 3).

6.1.1.3 Additional exposures of the Wakondo Tuff

In the Wasiriya beds of Rusinga Island, samples attributed to the Wakondo Tuff occur at the Wakondo locality (type sample CAT09-05 and two other minimally reworked deposits, CAT10-01 and LVP2013-16 (Fig. 2). At the Nyamita locality, the Wakondo Tuff is present as sample CAT09-01, a fresh, vitric tephra deposit at the base of the section at Nyamita 1 and a reworked and redeposited bed up-section sampled as CAT09-22 (Fig. 2). The Wakondo Tuff has not been found on Mfangano Island. At Karungu, the Wakondo Tuff is found at the northernmost section (Kisaaka North) sampled as KRU2012-15 (Fig. 4).

6.1.2 The Nyamita Tuff

The Nyamita Tuff is named after locally extensive but discontinuous ~ 1 km exposures of this deposit along the Nyamita Valley of Rusinga Island (Garrett et al., in press; Tryon et al., 2010; Van Plantinga, 2011). We follow Tryon et al. (2010) in using sample CAT09-21 from section Nyamita 2 in the Nyamita Valley as the type sample for this tuff (Figs. 2, 10c; Tryon et al. 2010).

6.1.2.1 Composition of the Nyamita Tuff

639

640 The type sample CAT09-21 is a 0.33-m-thick fresh, vitric deposit of unconsolidated grey
641 ash, found at the base of a ~3.5-m-thick massive deposit of the Nyamita Tuff (Fig. 10c;
642 Tryon et al., 2010). The type sample contains abundant grey glass shards generally 5 -
643 100 μ m. The Nyamita Tuff is a trachyphonolite (Fig. 7), with samples distinguished by
644 their consistent and low average Cl content of 0.16 ± 0.02 weight percent (Table 1, Fig. 9).
645 There is no evidence for reworking of the type deposit of the Nyamita Tuff.

646

647 6.1.2.2 Similarity coefficients of the Nyamita Tuff

648

649 SC values calculated between CAT09-21 and the randomized replicates of this sample
650 produced an average of 0.95 and a lower 95% confidence limit of 0.93 (Table 2).

651 Samples attributed to the Nyamita Tuff have SCs between 0.94 and 0.99 compared with
652 the type sample CAT09-21 (Table 3). Other samples compared with CAT09-21 have
653 SCs of ≤ 0.89 .

654

655 6.1.2.3 Additional exposures of the Nyamita Tuff

656

657 Field observations suggested that the Nyamita Tuff is the most common and widespread
658 tuff in the LVB, a hypothesis subsequently confirmed by chemical correlation. CAT09-
659 21 samples the freshest vitric tephra deposit from Rusinga Island's Nyamita Valley, but
660 this tuff can be physically traced laterally to section Nyamita 3, visually correlated using
661 a Jacobs staff and Abney level between all localities in Nyamita Valley, and chemically
662 correlated throughout the Nyamita Valley over a north-south transect for ~1 km (Garrett

et al., in press; Tryon et al., 2010; Van Plantinga, 2011:20). The present study demonstrates near ubiquity of the Nyamita Tuff at 21 of 32 measured sections in the eLVB, including 13 of 15 measured sections of Pleistocene exposures at Karungu (Figs. 4, 5, 6, 8). Although locally widespread on Rusinga Island, the Nyamita Tuff is absent from our studied exposures on Mfangano Island. At Karungu, the Nyamita Tuff occurs as a fresh, vitric tephra deposit in three samples (12KIS28, LVP2013-01 and LVP2013-04) in three measured sections at Kisaaka (KIS-10, Kisaaka Main and Kisaaka North respectively; Fig. 4). The bottom ~10-15 cm of the ~75-cm-thick tuffs from which these three samples were taken contain similar grey ash-sized grains, are powdery to the touch in hand samples, display abundant ~50-100 μ m angular glass shards visible at 40-100x magnification using a petrographic microscope, and are most commonly found in micro-lows on the landscape indicating that the basal portions of the tuffs were deposited by airfall and at most minimally reworked. The upper ~60 cm of these tuffs at sections KIS-10, Kisaaka Main and Kisaaka North are slightly more reworked deposits grey-brown to tan color, with a more silty texture in hand sample with small ~1 cm Mn-stained root casts and more detrital grains visible in thin section. Field observations show the Nyamita Tuff is laterally continuous for ~1 km at the locality of Kisaaka (Figs. 4, 10e) and at this specific locality chemical correlation confirms this lithostratigraphic correlation. Chemical correlations presented here show all samples from the laterally continuous units (KRU2012-10, KRU2012-11, KRU2012-13, 12KIS26, 12KIS28, LVP2013-01, LVP2013-02, CAT11-05, LVP2013-06, LVP2013-04, KRU2012-06) are chemically homogenous, unimodal and indistinguishable therefore constituting robust evidence for correlation. This laterally continuous exposure of the Nyamita Tuff at Kisaaka also drapes the gilgai topography of the paleosols on which it sits (Fig. 11). This

demonstrates laterally extensive evidence for airfall deposition, burial and preservation of the Nyamita Tuff at Kisaaka.

The presence of fresh, vitric tephra deposits of the Nyamita Tuff in the Nyamita Valley and at Kisaaka ~50 km to the south, the consistent chemical homogeneity of Nyamita Tuff samples and their stratigraphic position in relation to other marker beds make the Nyamita Tuff a locally useful lithostratigraphic marker (Fig. 8).

In addition to being widespread, Nyamita Tuff outcrops are the thickest of any tephra deposit in our sample, with a maximum observed thickness of ~4m at Nyamita and >2m in and around the Kisaaka North section of Karungu (Figs. 2, 4, 10c). The extent to which these thicknesses represent post-depositional sedimentary admixture is as yet undetermined. The Nyamita Tuff may represent either deposits of the largest eruption preserved in the eLVB, and/or a period of major changes in the local erosional and depositional regime.

6.1.3 The Nyamsingula Tuff

The Nyamsingula Tuff was first recognized at the Pleistocene exposures of the western Nyamsingula locality on Rusinga Island (Figs. 2, 7). Nyamsingula contains four laterally traceable outcrops of fresh, grey, vitric ash (CAT10-03, DP10-16, DP10-17, DP10-18) with indistinguishable compositions all attributed to the Nyamsingula Tuff (Fig. 2). We use a particularly fresh, vitric tephra deposit, sampled as CAT10-03 from near the base of

the 15-m-thick section DP10.14-DP10.15, as the type sample for the Nyamsingula Tuff (Figs. 2, 10d).

6.1.3.1 Composition of the Nyamsingula Tuff

In outcrop CAT10-03 is a 20cm-thick grey, vitric ash(Fig. 10d) of abundant grey glass with microscopic pumices, pumices fragments, some 50-200 μm , round to subround and slightly oval often overlapping vesicles. The Nyamsingula Tuff is a phonolite(Fig.7) and distinguished by its high average aluminum ($\text{Al}_2\text{O}_3 > 16.0 \text{ wt. } \%$), low average titanium ($\text{TiO}_2 \sim 0.45 \text{ wt. } \%$) and high average chlorine content ($\text{Cl} \sim 0.40 \text{ wt. } \%$) (Fig. 9, Table 1).

6.1.3.2 Similarity coefficients of the Nyamsingula Tuff

SC values calculated between CAT10-03 and the randomized replicates of this sample produced an average SC value of 0.93 and a lower 95% confidence limit of 0.89 (Table 2). All samples attributed to the Nyamsingula Tuff have a SC of 0.91 or greater compared to the type sample CAT10-03, and no other sample has a SC of over 0.87 compared to CAT10-03 (Table 3). Additionally, samples of Nyamsingula Tuff are consistently found stratigraphically above the Nyamita Tuff and below the Bimodal Trachyphonolitic Tuff.

6.1.3.3 Additional exposures of the Nyamsingula Tuff

On Rusinga Island the Nyamsingula Tuff is known only from the type locality, and it is not present on Mfangano Island. At the Karungu exposure this tuff is found at Kisaaka,

At the Kisaaka Main and KIS-10 sections, the Nyamsingula Tuff overlies the Nyamita Tuff (Fig. 4). At the RCS and ZTG sections at Kisaaka, modes 'b' of samples LVP2013-03 and LVP2013-07 are attributed to the Nyamsingula Tuff, admixed with glass from underlying deposits of the Nyamita Tuff, indicating local syn- or post-depositional reworking. Similar admixture of the glass of the Nyamsingula Tuff and Nyamita Tuff is seen at Aringo Section A (CAT11-02; Fig. 5). The Nyamsingula Tuff is also present at Obware at the WPT 212-214 section (Fig. 6). At Kisaaka Main and at Obware, the Nyamsingula Tuff is overlain by the Bimodal Trachyphonolitic Tuff (Figs. 4, 6, 8).

6.1.4 The Bimodal Trachyphonolitic Tuff (BTPT)

The BTPT is named for its distinctive composition. The representative sample chosen for this tuff is CAT11-07 from section Kisaaka Main at the locality of Kisaaka, Karungu because it contains abundant glass and the sample occurs in stratigraphic sequence with other named tuffs (Figs. 4, 8, 10e). Unlike the other three named tuffs discussed in this study, no example of fresh, vitric tephra for the BTPT have yet been found, and thus we do not designate a formal name and type locality. Samples attributed to the BTPT are always found as a ~10-50-cm-thick bed with varying degrees of pedogenic development, near the modern surface and often incorporated into paleosols. Bed thickness ranges from 10-55-cm, commonly with small (<5mm) Mn-stained root casts.

6.1.4.1 Composition of the BTPT

758

759 Despite their weathered appearance in outcrop and hand sample, all samples of the BTPT
760 preserve fresh glass of a distinctive grey-brown, green-brown or light brown color under
761 plane-polarized light. Glass occurring as microscopic pumices and pumice shards
762 sometimes over 200 μ m with round to stretched vesicles is common in most samples of
763 this tuff, but smaller shards 5-25 μ m occur. As the name suggests, this tuff is a
764 trachyphonolite (Fig. 7), with glass compositions divided into two chemically distinct
765 modes (Fig. 9, Table 1). One mode (CAT11-07a) is distinguished by low aluminum
766 content ($\text{Al}_2\text{O}_3 \sim 12.5$ wt. %) and high iron content ($\text{FeO} \sim 8-9$ wt %), and the second mode
767 (CAT11-07b) is distinguished by its higher aluminum content ($\text{Al}_2\text{O}_3 \sim 15.25$ wt %) and
768 lower iron content ($\text{FeO} \sim 6.5-6.75$ wt %). The bimodal nature of the BTPT is illustrated in
769 Figure 9. For clarity we label the low aluminum mode 'a' and the higher aluminum mode
770 'b' in all samples attributed to the BTPT (Fig. 9, Table 1). Each of these two
771 compositional modes is distinct from each other and from all other tephra samples found
772 in the eLVB (Fig. 9). The two compositional modes found in all samples of the BTPT
773 are petrographically distinct from all other glass shards in this study, but indistinguishable
774 from one another. These two modes exhibit glass chemistry indicative of density
775 dependent zonation of a magma chamber (Macdonald et al., 1994) and are always found
776 together whereas neither of the two modes is found in samples attributed to other tuffs
777 from the eLVB. For these reasons we interpret the bimodal composition of these samples
778 as the result of magmatic processes during eruption (cf. Shane et al., 2008) rather than
779 post-depositional mixing.

780

781 6.1.4.2 Similarity coefficients of the BTPT

782

783 SC values calculated between CAT11-07a and the 5000 randomized replicates of this
784 sample produced an average SC value of 0.95 and a lower 95% confidence limit of
785 0.92. The same procedure calculated for CAT11-07b produced an average SC value of
786 0.90 and a lower 95% confidence limit of 0.85 (Table 2). The lower SC values generated
787 here reflect the relatively high variability (standard deviations) of Al, Fe, and Ca oxides
788 measured in glasses from mode CAT11-07b. Previous studies note the difficulty in using
789 similarity coefficients with heterogeneous tephra deposits (Riehle et al., 2008). However,
790 all samples attributed to the BTPT share a mode 'a' similarity coefficient of 0.92 or
791 higher with the type sample CAT11-07a. No other sample has a SC of over 0.86
792 compared to CAT11-07a. All samples attributed to the BTPT also share a SC of ≥ 0.94
793 with the 'b' mode of the type sample CAT11-07b (Table 3). No other sample has a SC of
794 over 0.84 compared to CAT11-07b. The agreement of the SCs from both modes of the
795 BTPT (Table 3), the distinctive brown color of BTPT glass and consistent stratigraphic
796 observations in the field (Figs. 4, 6) make a strong case for correlation of these five tuffs
797 attributed to the BTPT.

798

799 6.1.4.3 Additional exposures of the BTPT

800

801 The BTPT is not currently known from Rusinga Island. It is present on Mfangano Island,
802 at the Walangani locality sampled as CAT10-05. It is also present at Karungu at Aoch
803 Nyasaya and Obware, in addition to the representative locality at Kisaaka (Figs. 5, 6). A
804 single sample from Obware, LVP2013-14, was found at the same stratigraphic level as
805 LVP2013-15 (Fig. 6), and based on our field lithostratigraphic correlation this tephra

deposit likely also correlates with the BTPT. While LVP2013-14b shares a SC of 0.94 with CAT11-07b, LVP2013-14a shares a SC of 0.89 with CAT11-07a, below the 95% lower confidence limit (Table 3). For this reason we refrain from confidently designating LVP2013-14 to the BTPT here, but note that the similarities of the glass color, stratigraphic position and the bimodal nature of the tuff suggest that it is adigenetically altered unit of the BTPT.

6.1.5 Unnamed trachytic tuffs of the Nyamita Valley

Two unnamed trachytic tuffs occur in the Nyamita Valley. The first was originally identified as a distinct mode of glass (CAT09-02a) from the upper-most tuff at section Nyamita 1 (Fig. 2, Tryon et al., 2010). Glass shards attributed to CAT09-02a are distinct based on major element oxide composition but are morphologically indistinguishable from shards attributed to CAT09-02b from the same tuff (Tryon et al., 2010). The CAT09-02a trachytic mode has lower magnesium and calcium contents than seen in any of the other trachytic tuffs in the eLVB (Table 1). We refrain from naming a tuff based on this mode, but we present SCs to show that it is distinct from all other tephras in this study. Randomization of mean element oxides from CAT09-02a produced an average SC value of 0.95 and a lower 95% confidence limit of 0.93 (Table 2).

A similar trachytic tuff was also identified in isolation (AV1004T5A) at another section, AV1004, further north in the Nyamita Valley (Van Plantinga, 2011, Fig. 2). At section AV1004 this tuff is stratigraphically below samples of the Nyamita Tuff (Van Plantinga, 2011, Figs. 2, 7). Backscattered electron imagery of glass from this tuff sample is

provided in Figure (11c). The relative similarity of glass from AV1004T5A to that from CAT09-05 at similar magnification demonstrates the need for chemical compositional data to differentiate these samples. SC values calculated between AV1004T5A and the 5000 randomized replicates of this sample produced an average SC value of 0.95 and a lower 95% confidence limit of 0.92 (Table 2).

The SC between sample AV1004T5A and CAT09-02a is just outside of the 95% confidence limit at 0.91 while SCs between either of these samples and every other tuff reported here is less than 0.86. CAT09-02a has a mean FeO of 9.39 wt. %, which is greater than 2 standard deviations above the mean FeO content of AV1004T5A (8.05 ± 0.14). Because of these differences, we refrain from diagnosing correlation here, but we note the overall chemical similarity of these tuffs and suggest they may represent tephras from a similar source, or perhaps one or more phases of the eruption leading to the Nyamita Tuff not found elsewhere. If more samples of similar trachytic glass are found, these samples may also prove to be end-members of a tuff with variable iron content, as is the case with the Nyamsingula Tuff.

6.1.6 Unnamed rhyolitic tuff

A rhyolitic tuff is known from a single sample, LVP2013-05, from near the base of section ZTG at Kisaaka, Karungu (Fig. 4). At this section LVP2013-05 forms a ~4.5-m-long, 0.17-m-thick lens of fresh, light-grey, vitric ash ~1 meter above the base of section and ~1.75m below the Nyamita Tuff. Sample LVP2013-05 is a fresh, vitric tephra deposit consisting of fine silt to clay-sized sediment dominated by abundant gray glass shards of

<5 μm – 20 μm . This is the only rhyolitic tephra deposit in our sample, categorically distinct from all other trachytic and phonolitic samples in this study (Fig. 7). SC values calculated between LVP2013-05 and the 5000 randomized replicates of this sample produced an average SC value of 0.85 and a lower 95% confidence limit of 0.76 (Table 2).

Rhyolitic sample LVP2013-05 from Kisaaka is compositionally similar to a sample of an obsidian source, MER 10, from Ololbutot 2 Oserion Farm, south of Lake Naivasha (SC = 0.83 with LVP2013-05; see Table 3; Fig. 1; Brown et al., 2013). The observed SC, although low because of high variation in rhyolites, is within the range of expected values for replicates of LVP2013-05 (Table 3) and all means of all major element oxides overlap at ± 1 standard deviation providing confident correlation (Brown and Nash, 2014). Analysis of the MER 10 obsidian sample, like all tuff samples analyzed for this study including LVP2013-05, were done on the same microprobe at the University of Utah using the same standards and protocols (Brown et al., 2013). As obsidians are effusive volcanics found close to their vent source, this correlation suggests that at least some of the tephra found at or near the base of the eLVB section originated from sources near Lake Naivasha in the central Kenyan rift.

6.1.7 A “Nyando Ash” from Songhor

We analyzed a single sample of the “Nyando Ashes” (Pickford, 1984) from the Pleistocene sediments of Songhor (X-5A-3) originally collected by McBrearty (1981) during her excavations there (Table 1, Fig. 1b-c). In thin section, X-5A-3 is gray silt-sized

sediment dominated by abundant $<5\ \mu\text{m} - 100\ \mu\text{m}$ glass shards with acutely angled margins and round to slightly oval vesicles. This tuff is a phonolite (Fig. 9), similar to the Wakondo and Nyamsingula Tuffs, but distinguishable from these other phonolites by lower Al_2O_3 ($\sim 13.75\ \text{wt}\%$) and higher FeO ($9.2\ \text{wt}\%$). This sample does not correlate with any other tuff known from the eLVB. SC values calculated between X-5A-3 and the 5000 randomized replicates of this sample produced average SC value of 0.96 and a lower 95% confidence SC limit of 0.93 (Table 2). No other sample analyzed here produced a SC value greater than 0.89 when compared to X-5A-3 (Table 3).

6.2 Optical dating results

The optical dating results for all five samples are presented in Table 4 and the D_e distributions are presented in Fig. S3 as radial plots. Ages of 46 ± 4 (RUP-1) and 50 ± 4 ka (RUP-2) were calculated for the samples collected above and below sample CAT09-21 (Fig. 2), providing age constraints for the deposition of the type sample of the Nyamita Tuff. Both ages are statistically consistent with each other at 1σ , and represent our best constraints on the depositional age of the Nyamita Tuff. The type sample, CAT09-21, around which the optical dating samples were collected, is a fresh vitric deposit indicating airfall deposition (Fig. 12) Thus, the depositional age likely closely approximates the eruptive age of the Nyamita Tuff.

For the samples from Wakondo, Bovid Hill locality, the ages range from 64 ± 6 (RUP-5) to 74 ± 6 ka (RUP-3) for samples from a channel complex that occurs $\sim 1\ \text{m}$ stratigraphically above the type sample of the Wakondo Tuff (CAT09-05) (Fig. 2; Jenkins et al, 2012). All three optical dating ages are statistically consistent with each

other at 1σ and there is no stratigraphic evidence to suggest that the sediments from which the samples were collected were deposited at different times. It is, therefore, our best estimate to obtain a weighted mean age of 68 ± 5 ka for the depositional age of the Bovid Hill locality channel complex from Wakondo. These age constraints provide a minimum age of 68 ± 5 ka for the deposition of the underlying Wakondo Tuff.

7. Discussion: Succession, age, and transport of the eLVB tephtras

We recognize a single sequence of tephtras among Pleistocene outcrops from Rusinga Island, Mfangano Island, and Karungu, exposed along a north-south transect of >60 km. From bottom to top, the sequence includes the Wakondo Tuff, the Nyamita Tuff, the Nyamsingula Tuff, and the Bimodal Trachyphonolitic Tuff (BTPT), with an additional three compositionally unique tephtras. Multiple radiometric dates bound the deposition of these tephtras and intercalated sediments to between ~ 100 ka and ~ 35 ka. Although tuffs may be locally correlated in the field where exposure is good, geochemical compositional data are required for accurate correlation between discontinuous outcrops and over longer distances between localities. No sample from Rusinga Island, Mfangano Island, or Karungu correlates with the “Nyando Ashes” from Songhor.

Tryon et al. (2010) hypothesized an origin in the Kenyan Rift (particularly Longonot and Suswa volcanoes, Fig. 1) for eLVB tephtras based on the absence of known Pleistocene-age volcanoes in Lake Victoria basin, the fine grain size of the ashes, and the restricted distribution of trachyte- and particularly phonolite-producing eruptions in East Africa during the Pleistocene. This hypothesis is empirically supported by our correlation of the distal rhyolitic ash sample LVP2013-05 to obsidian vent sources at Oserian Farm south

of Lake Naivasha in the Kenyan Rift (Fig. 1), 250 km east. These distant sources have important implications for understanding the depositional mode of the eLVB tephra and interpreting both their stratigraphic position and age.

The topography of the Mau escarpment on the western edge of the Kenyan Rift prevents rivers from running east-west between the eLVB and the Rift Valley volcanoes, eliminating the possibility for long-distance fluvial transport of the tephras, as is the case in the Lake Turkana Basin (Feibel, 2011). As suggested elsewhere (Tryon et al., 2010, 2012, 2014; Faith et al., in press), the Pleistocene sediments on Rusinga Island, Mfangano Island, and Karungu formed when Lake Victoria was absent or substantially diminished, excluding deposition or reworking by large scale lacustrine processes. Airfall deposition is thus the most likely method of transit for these tephras from the Kenyan Rift (or elsewhere) into the eLVB. Direct evidence for airfall deposition can be seen at Kisaaka, where the Nyamita Tuff drapes and preserves gilgai topography over ~1 km of lateral exposure (Fig. 11). In the rock record, gilgai topography is rarely preserved because the granular pedes of the A horizon in vertisols are easily transported and are often eroded during the next depositional event, truncating the characteristic undulations (Caudill et al., 1996; Driese and Mora, 1999; Driese et al., 2000, 2003). The preservation of the gilgai topography at Kisaaka demonstrates that airfall deposition of this tephra is preserved for at least some of the exposures of the Nyamita Tuff in the eLVB (Fig. 11).

Although there is evidence to indicate that at least some of the tephra are airfall deposits, the eLVB tephra were deposited on a landscape that included small, probably seasonally

active channels (Tryon et al., 2010, 2012, 2014) and springs (Beverly et al., in press).
Some deposits show clear evidence for reworking, including at least three deposits of the
Nyamita Tuff in the Nyamita Valley (Fig. 2), three deposits of Nyamita Tuff at Kisaaka
(Fig. 4) and a single deposit at Aringo Section A (Fig. 5). Such deposits are recognized on
the basis of chemically distinct, multimodal populations of glass shards, a mixture of
detrital clasts and volcanic glass, and/or evidence of pedogenesis, as is likely the case for
the upper portions of the Nyamita 2 section (Fig. 2). These processes indicate that the age
of the deposition of some tuffs may differ from the age of the eruption that produced
it. Where reworking occurs, it is most commonly between a chemically unimodal and
lithologically coherent unit of the Nyamita Tuff and some smaller, stratigraphically
superjacent tuff deposit. These redeposited units are easily recognized in the field based
on their lithology and evidence for pedogenesis. Chemically, the reworked tephra are
multimodal with one mode belonging to shards of the reworked Nyamita Tuff and the
other modes from the superjacent tuff deposit, usually the Nyamsingula Tuff (see Figs,
4,5), or the BTPT redeposited ~20 cm up-section in clumped clasts (Fig. 6).

While some syn- and post-depositional reworking of the ash occurred, such events are
distinguishable from primary deposition of the tuffs under consideration. For most tuffs
in this study, glass is chemically homogenous and fresh indicating rapid burial in an
environment where paleosol formation is a recurrent feature (e.g. Beverly et al., in press;
Van Plantinga, 2011). The documented airfall deposition of tuff units such as those at
Kisaaka, as well as the fairly rapid burial of such tuff units, facilitates lithostratigraphic
correlation between identified stratigraphic units at temporal scales (~10 to 10⁴ years), the
time scales widely employed in paleoecological and archaeological studies of ancient

974 landscapes (e.g., Potts et al., 1999; Behrensmeyer et al., 2000).

975

976 OSL dates bracketing the fresh vitric ash of the type sample of the Nyamita Tuff in
977 Rusinga Island's Nyamita Valley indicate an age of ~49 ka for its deposition there (see
978 Table 5 and supplementary information). Sedimentary features (e.g., the sample consists
979 almost entirely of glass shards) suggest that the dated deposit (CAT09-21) underwent
980 minimal reworking following deposition, and thus its depositional age likely
981 approximates eruption age (Fig. 12). We propose that this 49 ka date provides the earliest
982 age of deposition of the Nyamita Tuff in the Nyamita Valley of Rusinga Island. It also
983 likely reflects an approximate age for the continuous lateral deposits of the Nyamita Tuff
984 at Kisaaka, which drape the gilgai topography indicating they are airfall deposits (Figs 4,
985 11). Additionally, the 49 ka data for the Nyamita Tuff in the Nyamita Valley also
986 provides a maximum age for the other deposits of the Nyamita Tuff that were not
987 unequivocally deposited via airfall.

988

989 Glass shards from the ~2 m of overlying tuffaceous sediment (sampled in thin section as
990 CAT09-04 and analyzed as KRU2012-18) overlying the dated type sample (CAT09-21)
991 at Nyamita 2 are also chemically attributable to the Nyamita Tuff. However, glass from
992 the upper 2m at Nyamita2 occurs in a deposit that has undergone substantial post-
993 depositional turbation (Fig. 12) indicating a considerably different depositional history
994 than the underlying deposit from which CAT09-21 was taken and which is dated to 49
995 ka. Gastropods occur in the upper ~ 2m of the deposit, and one gastropod from the
996 deposited was dated using AMS radiocarbon to ~40.5 ka. Based on our field
997 observations, the gastropods at Nyamita 2 most likely burrowed into the tuff after

deposition, but before lithification. Thus, the minimum age for re-deposition of the reworked Nyamita Tuff at Nyamita 2 is ~40.5 ka, or <9 ka after deposition of the vitric, airfall deposit at the base of Nyamita 2. Radiocarbon dates on intrusive snail shells at adjacent Nyamita Tuff outcrops from the Nyamita Valley (Fig. 2) range from 33-45 ka (Table 5). These radiocarbon dates indicate that the Nyamita Tuff was reworked and redeposited throughout the Nyamita Valley >33 ka.

We interpret the widespread Nyamita Tuff as the most useful marker bed in the eLVB. Its position near the middle of the tephrosequence, its distinctive and relatively homogenous chemical composition and its OSL age estimate of ~49 ka for its initial deposition make it well suited as an informal boundary between upper and lower portions of the eLVB sedimentary sequence (Fig. 8). However, the age of the sediments above the Nyamita Tuff, including the Nyamsingula Tuff and BTPT, are poorly constrained. They postdate the ≤ 49 ka deposition of the Nyamita Tuff, and may fall into the 35-45 ka range of dates suggested by the gastropod shells, when snails were actively burrowing into the Nyamita Tuff, which formed the land surface (or near subsurface) at the time. Archaeological evidence provides further support for this inferred age, as all of the tuffaceous eLVB sediments contain only Middle Stone Age (MSA) artifacts, and no Later Stone Age (LSA) material has been found (Tryon et al., 2010, 2012, 2014; Faith et al., in press). Elsewhere in East Africa, MSA technologies are replaced by LSA ones during the same 35-45 ka interval (Tryon and Faith, 2013), and if the sediments were much younger than this we would expect to have recovered an LSA archaeological component above the Nyamita Tuff in sediment interbedded with the Nyamsingula Tuff and BTPT.

1022 Below the Nyamita Tuff, OSL dates of ~68 ka from the Wakondo locality, collected from
1023 sediments above the Wakondo Tuff, provide a minimum age for the deposition of the
1024 Wakondo Tuff (Tables 4, 5). U-series dates of 94.0 ± 3.3 ka and 111.4 ± 4.2 ka from tufa
1025 deposits at the base of the sequence at Nyamita (Beverly et al., in press; Fig. 2, Table 5)
1026 provide a maximum age for the deposition of the Wakondo Tuff, as well as for the entire
1027 sedimentary sequence. Compared to sediments above the Nyamita Tuff, which were
1028 likely deposited over ≤ 16 kyr (i.e. 33 – 49 ka), the lower portion of the tephrosequence
1029 appears to span a considerably longer interval, from ~49 ka - 100 ka.

1030

1031 The tephrostratigraphy presented here coupled with accompanying chronometric dates
1032 provides a robust and testable hypothesis for the depositional age of and correlation
1033 between late Pleistocene fossil- and artifact-bearing deposits on Rusinga and Mfangano
1034 Islands and near Karungu. The tephrostratigraphic framework supports our
1035 lithostratigraphic correlations between stratigraphic sections on Rusinga and at Karungu.
1036 Additionally, the tephrostratigraphy presented here allows the correlation of distant
1037 exposures over ~60 km. The tephrostratigraphic and chronometric framework presented
1038 here represents our hypothesis that dated and non-dated localities that have been
1039 correlated lithostratigraphically and/or using tephrostratigraphy are approximately
1040 contemporaneous. The hypothesis that the sedimentary deposits are contemporaneous can
1041 be further tested by constraining the eruptive age of tephras through a combination of
1042 correlation to more proximal, pumiceous facies and through methods that allow direct
1043 dating of the tephra (i.e., $^{40}\text{Ar}/^{39}\text{Ar}$, U/Pb).

1044

The tephrostratigraphic sequence presented herethus provides the initial basis for sampling spatial and temporal variation in paleoenvironments and hominin behaviors across ancient landscapes in the eLVB. Such an approach, with tephrostratigraphic correlation as one of many integrative tools, has proven highly successful though decades of research at Early and Middle Pleistocene deposits in the Turkana Basin, at Olorgesailie in Kenya, and at Olduvai Gorge, Tanzania (Ashley et al., 1999; Behrensmeyer et al., 2000; Blumenschine et al., 2008; Hay, 1976; Rogers et al., 1994; Stern, 1994; Potts et al., 1999). Our efforts in this direction are just beginning (Faith et al., in press; Garrett et al., in press; Tryon et al., 2014; Van Plantinga, 2011), and the tephrostratigraphy of the region presented here makes an important contribution towards the goal of developing a detailed chronostratigraphic framework of contemporaneous Late Pleistocene sites around the Lake Victoria Basin.

8. Conclusions

Analyses of distal tephras from the eLVB demonstrate the presence of eight distinct tephras of at least nine chemical compositions. Chemical characterization combined with field stratigraphy show that four of these tephras correlate over a distance >60 km: the Wakondo Tuff, the Nyamita Tuff, the Nyamsingula Tuff, and the Bimodal Trachyphonolitic Tuff (BTPT). Radiometric dates bound the tephrostratigraphic sequence. The base of the sequence is ~100 ka, based on U-series dates from tuffa deposits that underlie the entire sedimentary sequence (Beverly et al., in press). These dates also provide a maximum age for the deposition of the Wakondo Tuff, and OSL dates of ~68 ka from sediments above the Wakondo Tuff provide a minimum age for its

deposition. The Nyamita Tuff, which is bounded by OSL age estimates of 46 ± 4 (RUP-1) and 50 ± 4 ka (RUP-2) was likely deposited ~ 49 ka, a depositional age that may closely approximate its eruptive age. The Nyamsingula Tuff and the BTPT, which caps the sequence, were then deposited in sequence between ~ 49 and ≥ 35 ka, based on ^{14}C dates on gastropod shells that post-depositionally burrowed into the underlying Nyamita Tuff. The upper boundary of these sediments is poorly dated, but consistent with the available archaeological data. No Later Stone Age (LSA) artifacts have yet been recovered, and elsewhere in eastern Africa LSA assemblages appear ~ 45 -30 ka (Tryon and Faith, 2013).

Our correlations among the tephra and the age constraints provided by a variety of geochronological and other methods, demonstrate shared depositional sequences among disparate Pleistocene exposures from two islands in Lake Victoria and multiple exposures on the Kenyan mainland spanning ~ 35 -100 ka. This study broadly confirms the initial hypothesis of Pickford (1984) of widespread Pleistocene tephra deposits in the eLVB and a shared depositional history for Rusinga Island, Mfangano Island, and Karungu, but differs substantially in the details, particularly in the number of tephra present and the need for geochemical compositional data for reliable correlation.

This study further provides the stratigraphic control necessary for ongoing paleoenvironmental and human behavioral reconstructions based on fossils, soils, and artifacts from Pleistocene exposures in the eastern Lake Victoria Basin. Furthermore, we predict that the Wakondo Tuff, Nyamita Tuff, Nyamsingula Tuff, the BTPT, and other

eLVBdistal tephra deposits will be found in Pleistocene sediments in other depositional basins in East Africa, substantially expanding the scale of the work presented here.

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Figure Captions

Figure 1: Map of relevant eastern African Late Pleistocene archeological sites and major rift volcanoes. A. Outline of continent of Africa with box showing area of outset 'B'. B. Map of Lake Victoria region showing archaeological and paleontological localities discussed in the text and major volcanoes active during the Late Pleistocene. The dashed line indicates approximate mapped westward known extent of Rift Valley tephra. C. Map of approximate area of the eastern Lake Victoria Basin (eLVB) referenced in this study. This includes Rusinga Island, Mfangano Island, and Karungu and other Winam Gulf tephra and archeological sites.

Figure 2: Top Center: Map of Rusinga Island and Mfangano Island showing the extent of Pleistocene outcrops of the Wasiriya beds, the Waware beds as well as archaeological and paleontological localities discussed in the text (after Tryon et al., 2010, 2012). Below: Stratigraphic columns of measured and sampled sections, arranged west (on left) to east (right). Lithologies are indicated for all units. Tuffs with electron microprobe determined chemical composition are color-coded to compositional group and labeled with sample number (ex: CAT09-21). Tuffaceous units not chemically characterized and assigned are shown in grey. Dotted lines represent tuff units that can be traced laterally in the field between two or more measured sections.

Figure 3: Map of Karungu area around the town of Sorishowing localities of Pleistocene exposure: Aringo, Aoch Nyasaya, Kisaaka and Obware.

Figure 4: Above: Map of Kisaaka showing extent of Pleistocene exposure (after Beverly et al., in press) and locations of measured and sampled sections. Below: Stratigraphic columns of measured and sampled

1625 sections at Kisaaka, arranged southwest (on left) to northeast (right). Lithologies indicated for all units.
1626 Tuffs with electron microprobe determined chemical composition are color-coded to compositional group
1627 and labeled with sample number. Tuffaceous units not chemically characterized or assigned are shown in
1628 grey. Dotted lines represent tuff units that can be traced laterally in the field between two or more
1629 measured sections.

1630
1631 Figure 5: Right: Map of Aringo locality showing extent of Pleistocene exposure (after Beverly et al., in
1632 press) and locations of measured and sampled sections. Left: Stratigraphic columns of measured sections
1633 at Aringo, arranged south (on left) to north (right). Lithologies indicated for all units. Tuffs with electron
1634 microprobe determined chemical composition are color-coded to compositional group and labeled with
1635 sample number.

1636
1637 Figure 6: Center: Map of Aoch Nyasaya and Obware showing extent of Pleistocene exposure and locations
1638 of measured sections (after Beverly et al., in press). Left: Stratigraphic columns of measured sections at
1639 Aoch Nyasaya, arranged northwest (left) to southeast (right). Right: Measured section at Obware.
1640 Lithologies are indicated for all units. Tuffs with electron microprobe determined chemical composition
1641 are color-coded to compositional group and labeled with sample number. Dotted lines represent tuff units
1642 that can be traced laterally in the field between two or more measured sections. Sections were not
1643 measured for samples KRU2012-7 at Aoch Nyasaya or LVP2013-14 at Obware.

1644
1645 Figure 7: Schematic stratigraphic sections for all analyzed samples from the eastern Lake Victoria Basin.
1646 Composite section of Pleistocene tephra with unique colors corresponding to unique tephra named on the
1647 left of the figure. Individual tuff samples shown as rectangles with sample numbers for each sample at each
1648 Pleistocene locality listed on bottom right. Discrete chemical modes of glass found in a single sample

1649 shown as unique colors within a single rectangle. Tuffs with glass shards of multiple compositions due to
1650 mechanical mixing have colors separated with a vertical line. Tuffs with distinct modes of glass as a
1651 product of magmatic processes during eruption have colors representing modes separated by a diagonal
1652 line. Grey rectangles are tuff samples lacking good chemical analysis. Dotted lines represent tuff units that
1653 can be traced laterally in the field between two measured sections. White area represents non-
1654 volcanoclastic sediments not used for correlation.

1655

1656 Figure 8: Total-alkali Silica graph (after Le Bas et al., 1986) of type samples of all eight distinct tuffs
1657 discussed in this study along with obsidian samples from the Kenya Rift. All obsidian data are from Brown
1658 et al. (2013).

1659

1660 Figure 9: Bivariate plot of Cl against TiO_2 for means of all samples discussed in this study.

1661

1662 Figure 10: (A) Photograph of the Wakondo Tuff at Wakondo, Rusinga Island. (B) Note the fresh grey vitric
1663 character of the tuff in close-up view of the outcrop. (C) Photograph of the type section Nyamita 2 from the
1664 Nyamita Valley, Rusinga Island. The type sample of the Nyamita Tuff, CAT09-21, taken from the fresh,
1665 vitric tephra deposit at the base of the tuff in this section is indicated. OSL samples RUS-1 and RUS-2
1666 bracketing CAT09-21 also indicated. (D) Photograph of sample CAT10-03, type sample of the
1667 Nyamsingula Tuff, from section DP10.14-DP10.15 at the locality of Nyamsingula, Rusinga Island. Note
1668 the fresh grey, ashy fine texture of the fresh, vitric tephra deposit and the discrete contrast with the
1669 overlying soil. (E) Panoramic photograph of the section Kisaaka Main and the surrounding exposure
1670 showing (from bottom to top) the Nyamita Tuff (LVP2013-01, 02), the Nyamsingula Tuff (LVP2013-08)

1671 and the representative sample (CAT11-07) of the BTPT in stratigraphic sequence. Also note the lateral
1672 extent of the Nyamita Tuff at Kisaaka.

1673

1674 Figure 11: Photographs of the Nyamita Tuff exposed throughout the locality of Kisaaka (modified
1675 from Beverly et al., in review). The Nyamita Tuff drapes gilgai topography of the paleo-Vertisol. This
1676 topography is formed when the smectitic clays of Vertisols shrink and swell with the wet and dry seasons.
1677 The rapid airfall deposition of the tuff preserved these micro-highs and lows on the landscape from fluvial
1678 truncation.

1679

1680 Figure 12: Photomicrographs of resin-impregnated thin sections from samples CAT09-21 (bottom) and
1681 CAT09-04 (top) collected from the Nyamita 2 stratigraphic section in the Nyamita Valley, Rusinga Island,
1682 shown in stratigraphic order. Stratigraphic positions of samples are shown in Figures 2, 10c. Basal sample
1683 CAT09-21 is fresh vitric tephra composed almost entirely of volcanic glass shards (dark spots on
1684 photomicrograph are voids or bubbles formed during sample preparation) and some secondary calcite is
1685 present. The OSL samples RUS 1 is from directly above CAT09-21 and dated 46 ± 4 ka and RUS 2 from
1686 directly below CAT09-21 and is dated 50 ± 4 ka. This sample is interpreted as a primary fallout tephra that
1687 has been, at most, minimally reworked. Overlying sample CAT09-04 is a reworked and bioturbated portion
1688 of the same deposit, with sparse glass shards set in a silt-clay matrix with epiclastic minerals and lithic
1689 fragments. All glass shards in these samples are attributed to the Nyamita Tuff on the basis of geochemical
1690 composition (CAT09-04 was analysed on the microprobe as 'KRU2012-18').

1 Table 1: Mean major and minor element oxides by weight percent. One standard deviation from the mean listed below each element oxide mean.

Wakondo Tuff	No	M,N	SiO ₂	TiO ₂	ZrO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	F	Cl	Sum	less O	Sum less O	H ₂ O	Total
CAT09-05	17	1,1	61.67	0.54	0.07	15.51	7.97	0.36	0.32	1.02	9.01	4.75	0.46	0.31	102.00	0.26	101.73	0.03	100.87
			1.39	0.09	0.04	0.28	0.19	0.02	0.02	0.03	0.54	0.51	0.19	0.01	2.36	0.08	2.41	0.88	1.88
CAT09-01	20	1,1	60.56	0.51	0.08	15.65	8.11	0.36	0.33	1.04	9.18	4.79	0.38	0.31	101.32	0.23	101.09	0.62	100.81
			1.03	0.09	0.05	0.15	0.14	0.03	0.02	0.04	0.24	0.26	0.06	0.02	1.15	0.03	1.14	0.88	0.47
CAT09-22	11	1,1	58.73	0.56	0.07	15.28	7.41	0.31	0.33	1.02	9.12	4.61	0.25	0.28	97.97	0.17	97.80	2.27	99.24
			0.81	0.09	0.07	0.28	0.42	0.04	0.02	0.03	1.08	0.50	0.11	0.02	1.14	0.05	1.11	0.80	0.79
CAT10-01	18	1,1	61.53	0.56	0.09	15.34	7.94	0.36	0.32	1.02	8.73	4.50	0.27	0.31	100.97	0.18	100.78	-0.30	99.60
			2.26	0.06	0.04	0.34	0.22	0.03	0.02	0.06	0.76	0.72	0.04	0.02	3.71	0.02	3.72	1.31	2.81
KRU2012-15	18	1,1	57.23	0.52	0.08	15.41	7.78	0.35	0.33	0.98	8.34	4.30	0.44	0.31	96.07	0.25	95.81	5.63	100.58
			2.15	0.06	0.04	0.38	0.22	0.02	0.02	0.04	0.88	0.84	0.11	0.01	4.13	0.05	4.14	1.60	2.72
CRJ11-27	8	1,1	59.50	0.59	0.12	16.04	8.05	0.35	0.33	1.09	5.96	1.76	0.39	0.32	94.51	0.23	94.27	3.87	97.25
			1.30	0.08	0.02	0.21	0.19	0.03	0.02	0.05	0.59	1.02	0.17	0.01	2.15	0.07	2.14	1.71	0.88
CRJ11-28	8	1,1	59.39	0.62	0.11	15.77	8.03	0.33	0.34	1.05	5.53	1.88	0.40	0.29	93.73	0.23	93.49	3.78	96.39
			0.73	0.09	0.03	0.21	0.17	0.03	0.02	0.04	1.00	1.22	0.23	0.03	2.83	0.10	2.83	1.57	1.55
LVP2013-16	10	1,1	62.07	0.55	0.10	15.61	8.34	0.36	0.35	1.10	8.67	4.93	0.52	0.28	102.89	0.28	102.61	0.24	101.91
			1.51	0.06	0.05	0.56	0.50	0.02	0.03	0.10	1.08	0.31	0.25	0.02	3.47	0.10	3.55	1.50	2.10
Nyamita Tuff	No	M,N	SiO ₂	TiO ₂	ZrO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	F	Cl	Sum	less O	Sum less O	H ₂ O	Total
CAT09-21	21	1,1	64.38	0.59	0.05	15.62	6.76	0.29	0.36	1.13	7.73	5.02	0.26	0.17	102.36	0.15	102.21	-0.66	100.80
			1.16	0.08	0.04	0.14	0.13	0.03	0.02	0.04	0.28	0.42	0.15	0.01	1.51	0.06	1.49	1.09	0.53
CAT09-02b	12	1,2	62.03	0.58	0.04	15.55	6.78	0.29	0.36	1.13	7.58	4.83	0.13	0.18	99.47	0.09	99.38	1.46	100.08
			1.54	0.08	0.05	0.16	0.17	0.03	0.01	0.03	0.39	0.39	0.05	0.02	2.13	0.02	2.14	0.86	1.55
CAT09-03	27	1,1	60.47	0.58	0.07	15.87	6.86	0.29	0.36	1.20	7.14	4.54	0.27	0.17	97.81	0.15	97.66	1.41	98.31
			1.31	0.09	0.04	0.49	0.10	0.03	0.02	0.05	0.69	1.24	0.10	0.02	2.71	0.04	2.71	1.16	2.15
CAT 11-01	17	1,1	59.99	0.60	0.06	15.32	6.62	0.27	0.36	1.10	7.72	4.79	0.09	0.18	97.09	0.08	97.01	3.13	99.40
			1.88	0.10	0.04	0.37	0.16	0.03	0.01	0.05	0.56	0.37	0.04	0.02	2.91	0.02	2.91	1.50	1.70
CAT11-02a	19	1,2	60.04	0.55	0.06	15.47	6.58	0.28	0.35	1.11	7.69	5.06	0.27	0.16	97.62	0.15	97.47	3.31	100.05
			1.42	0.08	0.04	0.36	0.55	0.05	0.04	0.07	0.33	0.58	0.13	0.02	2.13	0.06	2.12	1.38	1.13

CAT11-05	16	1,1	59.37	0.58	0.08	16.03	6.93	0.37	0.37	1.18	5.32	1.72	0.24	0.18	92.38	0.14	92.23	3.42	94.88
			1.82	0.08	0.05	0.48	0.27	0.11	0.02	0.06	1.13	0.92	0.20	0.01	3.55	0.08	3.52	1.43	2.38
KRU2012-01	19	1,1	61.28	0.57	0.05	15.50	6.48	0.28	0.34	1.11	7.68	4.99	0.08	0.16	98.51	0.07	98.44	2.44	100.16
			1.25	0.10	0.05	0.28	0.57	0.03	0.04	0.08	0.39	0.26	0.06	0.02	1.53	0.03	1.53	1.07	1.07
KRU2012-02	20	1,1	60.68	0.60	0.08	15.29	6.55	0.26	0.33	1.06	7.41	4.80	0.08	0.16	97.30	0.07	97.23	2.81	99.31
			0.98	0.11	0.04	0.40	0.54	0.06	0.07	0.23	1.28	1.41	0.05	0.04	2.27	0.03	2.26	1.55	1.07
KRU2012-03	19	1,1	54.76	0.63	0.05	15.84	6.79	0.28	0.37	1.10	7.67	4.57	0.30	0.16	92.54	0.16	92.38	9.13	100.75
			2.15	0.08	0.04	0.13	0.15	0.03	0.02	0.04	0.33	0.56	0.13	0.01	2.64	0.06	2.65	1.33	1.47
KRU2012-06	20	1,1	56.31	0.61	0.04	15.47	6.68	0.27	0.37	1.05	7.40	4.36	0.27	0.18	93.00	0.15	92.84	7.83	99.93
			2.42	0.07	0.04	0.64	0.20	0.03	0.03	0.09	0.81	0.75	0.10	0.03	4.38	0.04	4.39	1.33	3.42
KRU2012-07	14	1,1	60.14	0.61	0.04	15.42	6.95	0.27	0.36	1.12	7.83	4.98	0.12	0.17	98.01	0.09	97.92	1.97	99.12
			1.29	0.06	0.04	0.38	0.17	0.03	0.03	0.04	0.50	0.33	0.05	0.01	2.03	0.02	2.02	1.20	1.97
KRU2012-10	16	1,1	59.08	0.56	0.02	15.89	6.84	0.28	0.36	1.12	7.63	4.76	0.27	0.16	96.97	0.15	96.82	5.83	101.48
			1.20	0.06	0.05	0.30	0.12	0.03	0.01	0.04	0.47	0.64	0.05	0.01	2.18	0.02	2.19	1.10	1.58
KRU2012-11	18	1,1	58.79	0.60	0.05	15.72	6.77	0.27	0.36	1.08	7.59	4.16	0.29	0.17	95.53	0.16	95.37	7.15	102.12
			1.18	0.06	0.05	0.19	0.12	0.03	0.01	0.06	0.53	0.63	0.07	0.02	2.07	0.03	2.06	0.94	1.68
KRU2012-13	18	1,1	57.90	0.56	0.05	15.61	6.75	0.30	0.36	1.09	7.36	4.23	0.35	0.17	94.72	0.18	94.54	7.00	100.79
			1.78	0.08	0.04	0.39	0.15	0.03	0.03	0.05	0.53	0.65	0.21	0.02	2.96	0.09	2.96	1.14	2.34
KRU2012-16	18	1,1	59.56	0.57	0.04	15.82	6.67	0.28	0.35	1.09	7.90	4.86	0.31	0.18	97.63	0.17	97.46	4.73	101.45
			1.02	0.08	0.08	0.19	0.22	0.03	0.04	0.04	0.42	0.41	0.11	0.06	1.50	0.06	1.48	1.22	0.65
KRU2012-17	17	1,1	59.14	0.58	0.04	15.75	6.63	0.28	0.36	1.08	7.62	4.11	0.37	0.17	96.13	0.19	95.94	4.82	100.02
			1.49	0.07	0.05	0.16	0.13	0.03	0.02	0.03	0.37	0.48	0.17	0.01	2.05	0.07	2.07	1.38	1.04
KRU2012-18	10	1,1	61.47	0.56	0.08	15.40	6.55	0.28	0.38	1.08	7.37	4.77	0.47	0.17	98.59	0.24	98.35	2.76	100.37
			1.92	0.09	0.04	0.51	0.42	0.03	0.11	0.07	0.72	0.27	0.17	0.02	3.53	0.07	3.53	1.68	2.19
LVP2013-01	20	1,1	62.18	0.59	0.08	15.92	6.67	0.30	0.35	1.13	6.98	5.11	0.44	0.17	99.93	0.22	99.71	2.28	101.24
			0.95	0.04	0.04	0.27	0.22	0.02	0.01	0.05	0.36	0.22	0.17	0.01	1.67	0.07	1.73	1.04	1.63
LVP2013-02	19	1,1	62.13	0.58	0.10	15.89	6.71	0.28	0.33	1.10	7.09	5.01	0.44	0.17	99.82	0.22	99.60	2.70	101.55
			0.75	0.05	0.04	0.14	0.08	0.03	0.04	0.09	0.50	0.21	0.08	0.02	1.35	0.04	1.35	1.32	0.58
LVP2013-03a	3	1,2	62.48	0.59	0.06	15.97	6.73	0.27	0.34	1.12	6.99	5.24	0.42	0.16	100.38	0.21	100.17	2.11	101.53
			0.36	0.03	0.03	0.10	0.10	0.01	0.01	0.04	0.23	0.14	0.02	0.00	0.68	0.01	0.69	0.92	0.24
LVP2013-04	20	1,1	61.41	0.60	0.08	15.56	6.57	0.29	0.36	1.11	6.90	5.06	0.46	0.16	98.56	0.23	98.33	2.65	100.25
			0.80	0.04	0.04	0.25	0.10	0.03	0.02	0.05	0.35	0.22	0.06	0.01	1.38	0.02	1.38	1.15	1.02
LVP2013-06	20	1,1	61.75	0.59	0.09	15.82	6.61	0.29	0.36	1.10	6.92	5.15	0.44	0.16	99.28	0.22	99.06	2.34	100.67

			1.01	0.03	0.06	0.24	0.14	0.03	0.02	0.04	0.26	0.20	0.05	0.01	1.62	0.02	1.63	1.32	1.05
LVP2013-07a	14	1,2	62.25	0.60	0.10	15.98	6.55	0.28	0.36	1.08	6.83	5.12	0.49	0.16	99.80	0.24	99.56	1.77	100.60
			1.32	0.05	0.04	0.33	0.14	0.02	0.01	0.06	0.38	0.23	0.17	0.02	2.14	0.07	2.19	1.50	1.14
LVP2013-11	16	1,1	63.25	0.59	0.10	16.28	6.56	0.31	0.36	1.15	7.12	5.19	0.45	0.16	101.52	0.23	101.29	1.23	101.79
			0.74	0.05	0.05	0.21	0.39	0.04	0.02	0.06	0.37	0.24	0.10	0.01	1.37	0.04	1.39	1.69	0.90
12KIS26	16	1,1	62.96	0.58	0.09	16.27	6.44	0.29	0.36	1.15	6.87	5.08	0.46	0.17	100.73	0.23	100.49	2.35	102.12
			1.08	0.03	0.04	0.22	0.10	0.06	0.02	0.07	0.35	0.23	0.06	0.02	1.62	0.03	1.62	1.48	0.64
12KIS28	13	1,1	62.82	0.61	0.08	16.13	6.56	0.30	0.37	1.11	7.04	5.01	0.53	0.17	100.72	0.26	100.45	0.02	99.75
			1.72	0.04	0.04	0.36	0.15	0.03	0.02	0.05	0.45	0.26	0.12	0.01	2.78	0.05	2.80	0.01	2.79
Nyamsingula Tuff	No	M,N	SiO₂	TiO₂	ZrO₂	Al₂O₃	FeO	MnO	MgO	CaO	Na₂O	K₂O	F	Cl	Sum	less O	Sum less O	H₂O	Total
CAT10-03	15	1,1	58.16	0.45	0.18	16.22	6.73	0.30	0.27	0.99	9.24	5.00	0.61	0.40	98.57	0.35	98.22	3.54	101.01
			1.16	0.06	0.04	0.29	0.34	0.03	0.04	0.06	0.44	0.40	0.12	0.06	1.49	0.06	1.48	0.87	0.79
CAT11-02b	6	2,2	59.88	0.41	0.18	15.83	7.18	0.33	0.19	1.03	8.97	4.73	0.44	0.38	99.55	0.27	99.28	1.35	99.83
			0.62	0.06	0.03	0.20	0.27	0.05	0.02	0.06	0.44	0.20	0.07	0.05	1.23	0.04	1.23	1.06	0.50
DP10-16	20	1,1	58.84	0.44	0.19	16.31	6.60	0.30	0.30	1.02	8.99	5.05	0.58	0.39	99.02	0.33	98.69	2.56	100.51
			1.11	0.04	0.06	0.31	0.40	0.03	0.04	0.08	0.46	0.47	0.09	0.07	1.42	0.05	1.40	0.92	0.73
DP10-17	15	1,1	59.14	0.43	0.18	16.30	6.45	0.29	0.28	1.02	9.29	4.82	0.59	0.40	99.19	0.34	98.85	2.73	100.87
			0.81	0.08	0.05	0.27	0.18	0.04	0.02	0.04	0.44	0.32	0.10	0.04	1.49	0.05	1.47	0.62	1.19
DP10-18	17	1,1	59.41	0.45	0.19	16.31	6.34	0.28	0.29	1.03	9.04	4.98	0.58	0.38	99.27	0.33	98.94	2.58	100.82
			0.84	0.08	0.04	0.17	0.12	0.03	0.04	0.03	0.63	0.25	0.17	0.04	1.47	0.08	1.44	1.02	0.89
LVP2013-3b	31	2,2	60.94	0.44	0.22	16.17	7.16	0.33	0.19	1.01	8.06	4.89	0.81	0.38	100.59	0.43	100.16	1.96	101.32
			0.98	0.04	0.06	0.23	0.23	0.03	0.02	0.08	0.45	0.28	0.13	0.05	1.51	0.06	1.53	1.18	1.06
LVP2013-7b	6	2,2	61.17	0.44	0.21	16.32	7.14	0.32	0.19	1.00	7.93	4.88	0.78	0.40	100.78	0.42	100.36	1.98	101.54
			0.40	0.05	0.04	0.14	0.11	0.02	0.02	0.07	0.54	0.13	0.09	0.05	1.07	0.05	1.09	0.95	0.49
LVP2013-8	13	1,1	60.99	0.45	0.21	16.16	7.04	0.32	0.20	1.02	7.62	4.82	0.75	0.36	99.93	0.40	99.53	1.80	100.55
			2.00	0.05	0.04	0.61	0.27	0.03	0.03	0.08	0.70	0.28	0.07	0.04	3.56	0.03	3.58	1.31	2.68
LVP2013-13	12	1,1	61.39	0.46	0.24	16.99	6.41	0.30	0.31	1.03	7.57	5.14	0.78	0.36	100.98	0.41	100.57	2.17	102.02
			1.56	0.05	0.06	0.42	0.31	0.02	0.04	0.07	0.80	0.29	0.10	0.07	2.35	0.06	2.38	1.35	1.48
12KIS34	19	1,1	60.32	0.43	0.22	16.15	7.01	0.31	0.21	1.03	7.89	4.79	0.89	0.39	99.65	0.46	99.19	2.78	101.18
			1.65	0.10	0.07	0.33	0.30	0.03	0.08	0.15	0.70	0.32	0.27	0.11	2.44	0.13	2.49	1.47	1.69

BTPT	No	M,N	SiO ₂	TiO ₂	ZrO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	F	Cl	sum	less O	Sum less O	H ₂ O	Total
CAT11-07a	7	1,2	62.25	0.66	0.10	12.72	9.14	0.44	0.20	0.99	8.20	4.76	0.38	0.26	100.11	0.22	99.89	0.72	99.60
			0.52	0.11	0.07	0.14	0.18	0.04	0.01	0.05	0.25	0.17	0.12	0.02	0.82	0.05	0.83	0.58	0.35
CAT11-07b	13	2,2	61.92	0.81	0.02	15.22	7.07	0.33	0.43	1.40	7.25	5.46	0.20	0.11	100.21	0.11	100.10	1.14	100.46
			0.86	0.11	0.04	0.30	0.39	0.04	0.08	0.11	0.46	0.17	0.20	0.02	1.28	0.09	1.22	0.71	0.79
CAT10-05a	9	1,2	62.24	0.69	0.12	12.64	9.01	0.44	0.21	0.97	7.08	4.44	0.51	0.26	98.61	0.27	98.34	0.53	97.86
			0.43	0.03	0.03	0.14	0.19	0.03	0.02	0.04	0.51	0.16	0.06	0.02	1.05	0.03	1.04	0.67	0.77
CAT10-05b	3	2,2	61.28	0.79	0.04	15.23	6.94	0.36	0.43	1.37	6.21	5.43	0.32	0.11	98.51	0.16	98.35	0.10	97.68
			1.73	0.07	0.02	0.50	0.24	0.03	0.02	0.07	0.27	0.23	0.02	0.03	3.06	0.01	3.07	1.14	1.93
LVP2013-09a	15	1,2	64.03	0.68	0.13	13.33	8.97	0.44	0.21	1.05	7.45	4.64	0.62	0.24	101.79	0.32	101.47	0.25	100.73
			0.85	0.06	0.04	0.47	0.49	0.04	0.03	0.11	0.40	0.15	0.12	0.02	1.28	0.05	1.26	0.79	1.23
LVP2013-09b	12	2,2	62.97	0.78	0.06	15.74	7.00	0.35	0.42	1.40	6.50	5.36	0.43	0.10	101.10	0.20	100.90	1.12	101.24
			0.86	0.06	0.05	0.35	0.41	0.04	0.06	0.08	0.34	0.13	0.06	0.02	1.15	0.03	1.14	1.44	1.35
LVP2014-10a	14	1,2	62.66	0.66	0.12	12.78	8.86	0.43	0.20	0.97	7.37	4.63	0.54	0.26	99.49	0.29	99.20	-0.21	98.00
			1.49	0.07	0.04	0.40	0.50	0.05	0.04	0.09	0.68	0.16	0.06	0.02	2.23	0.03	2.22	1.22	2.15
LVP2014-10b	6	2,2	62.05	0.78	0.02	15.50	6.84	0.34	0.41	1.38	6.52	5.37	0.33	0.10	99.64	0.16	99.48	0.20	98.92
			0.47	0.07	0.03	0.37	0.24	0.04	0.07	0.08	0.43	0.18	0.04	0.02	0.90	0.02	0.89	1.10	0.62
LVP2014-14a	7	1,2	63.81	0.65	0.13	12.57	8.24	0.34	0.13	0.98	6.39	4.61	0.47	0.25	98.57	0.25	98.32	1.22	98.62
			1.04	0.04	0.06	0.47	0.37	0.03	0.02	0.08	0.26	0.22	0.06	0.04	1.54	0.03	1.53	1.16	0.83
LVP2014-14b	13	2,2	62.10	0.77	0.05	14.73	6.78	0.31	0.37	1.45	5.79	5.30	0.32	0.11	98.07	0.16	97.91	1.20	98.35
			1.77	0.10	0.05	0.55	0.44	0.04	0.13	0.13	0.48	0.35	0.07	0.03	2.46	0.03	2.47	1.78	1.24
LVP2013-15a	5	1,2	65.25	0.63	0.12	13.25	8.73	0.40	0.18	1.09	6.81	4.66	0.54	0.24	101.89	0.28	101.61	0.38	101.01
			1.72	0.03	0.08	0.62	0.54	0.04	0.13	0.17	1.01	0.23	0.08	0.03	1.70	0.03	1.68	1.65	0.39
LVP2013-15b	21	2,2	63.20	0.77	0.05	15.33	6.82	0.31	0.41	1.52	6.20	5.42	0.37	0.10	100.50	0.18	100.32	2.49	102.05
			1.27	0.04	0.04	0.47	0.36	0.04	0.10	0.09	0.26	0.16	0.05	0.02	1.42	0.02	1.41	1.48	0.54
Unique Tuffs	No	M,N	SiO ₂	TiO ₂	ZrO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	F	Cl	Sum	less O	Sum less O	H ₂ O	Total
AV1004T5A	15	1,1	63.83	0.52	0.20	10.80	8.05	0.35	0.14	0.66	7.16	3.74	0.65	0.31	96.41	0.34	96.06	1.57	96.73
			2.08	0.07	0.04	0.16	0.14	0.03	0.03	0.02	0.83	0.52	0.17	0.02	2.90	0.07	2.90	1.46	1.88
CAT09-02a	5	1,2	64.80	0.62	0.17	10.51	9.39	0.37	0.13	0.68	7.54	3.31	0.56	0.35	98.44	0.32	98.12	1.23	98.30

			1.00	0.08	0.07	0.12	0.22	0.02	0.01	0.03	0.72	0.79	0.04	0.01	2.43	0.02	2.42	1.30	1.25
X-5A-3	14	1,1	57.90	0.63	0.15	13.75	9.20	0.43	0.37	1.22	8.39	4.81	0.53	0.21	97.62	0.27	97.34	0.48	96.80
			1.46	0.07	0.06	0.14	0.19	0.03	0.01	0.04	0.38	0.17	0.09	0.02	1.49	0.04	1.49	0.77	0.81
LVP2013-05	14	1,1	71.21	0.13	0.41	10.30	3.96	0.06	0.02	0.10	4.75	4.14	1.18	0.44	96.70	0.60	96.11	4.62	100.29
			0.95	0.03	0.07	0.43	0.19	0.02	0.01	0.04	0.22	0.13	0.11	0.04	1.15	0.05	1.17	0.61	1.05

2 Table 2: Representative or type samples of the named tuffs and discrete chemical modes discussed in this
3 study GPS coordinates for each type or representative sample or mode provided. Results of randomization
4 of type sample or mode means and standard deviations to determine mean similarity coefficient values and
5 lower 95% similarity coefficient confidence limits.

Tuff	Type Sample	GPS coords (WGS 1984)	SC 7 element oxides used in this study	
			Mean	Lower 95% Confidence Limit
Wakondo	CAT09-05	S 00°25.565' E 034°10.347'	0.95	0.93
Nyamita	CAT09-21	S 00°25.246' E 034°09.599'	0.95	0.93
Nyamsingula	CAT10-03	S 00°24.706' E 034°11.126'	0.93	0.89
BTPT Mode A	CAT11-07a	S 00°48.342' E 034°08.216'	0.95	0.92
BTPT Mode B	CAT11-07b	S 00°48.342' E 034°08.216'	0.90	0.85
Nyamita Valley Trachytic Tuff	AV1004T5A	S 00°25.584' E 034°09.554'	0.95	0.92
Nyamita Valley Trachytic Tuff	CAT09---02a	S 00°25.369' E 034°09.615'	0.96	0.93
Songhor	X-5A -3	S 00°03.324' E 035°13.084'	0.96	0.94
Rhyolite	LVP2013-05	S 00°48.278' E 034°08.274'	0.85	0.76

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Table 3: Similarity coefficients for all distinct modes of samples analyzed in this study based on the restricted seven-element list. Samples listed vertically (left) and compared with the type samples of every chemically unique tuff or mode listed horizontally (top). Lower 95% confidence limit for each type sample or mode listed in parentheses. Colored squares are samples or modes with similarity coefficient $\geq$ the 95% lower confidence limit determined by randomization when compared to the type sample and overlap at two standard deviations for the seven element oxides used for correlation when compared to the type sample. Black squares are the type sample or mode compared to itself.

	Wakondo Tuff CAT09- 05 (.93)	Nyamita Tuff CAT09- 21 (.93)	Nyamsingula Tuff CAT10-03 (.89)	BTPT 'a' CAT11- 07a (.92)	BTPT 'b' CAT11- 07b (.85)	AV1004 T5A (.92)	CAT09- 02a (.93)	Songhor Tuff X-5A-3 (.93)	Rhyolitic Tuff LVP2013- 05 (.76)
CAT09-05		0.85	0.87	0.82	0.75	0.81	0.76	0.83	0.35
CAT09-01	0.98	0.85	0.86	0.81	0.75	0.81	0.75	0.83	0.35
CAT09-22	0.95	0.89	0.87	0.82	0.78	0.77	0.73	0.83	0.35
CAT10-01	0.99	0.85	0.86	0.83	0.76	0.81	0.77	0.84	0.35
KRU2012-15	0.98	0.85	0.87	0.82	0.76	0.82	0.75	0.82	0.35
CRJ11-27	0.96	0.87	0.85	0.82	0.77	0.79	0.77	0.85	0.35
CRJ11-28	0.95	0.88	0.85	0.83	0.78	0.78	0.76	0.85	0.34
LVP2013-16	0.95	0.87	0.83	0.83	0.77	0.78	0.75	0.87	0.33
CAT09-21	0.85		0.83	0.75	0.83	0.68	0.66	0.85	0.32
CAT09-02a	0.85	0.99	0.83	0.74	0.82	0.68	0.65	0.84	0.32
CAT09-03	0.83	0.97	0.81	0.73	0.84	0.67	0.64	0.85	0.31
CAT 11-01	0.84	0.97	0.81	0.74	0.82	0.67	0.65	0.84	0.32
CAT11-02a	0.85	0.96	0.83	0.73	0.81	0.68	0.64	0.82	0.32
CAT11-05	0.86	0.94	0.79	0.76	0.83	0.69	0.68	0.89	0.31
KRU2012-01	0.85	0.96	0.82	0.73	0.81	0.68	0.64	0.82	0.32
KRU2012-02	0.84	0.94	0.81	0.74	0.81	0.67	0.65	0.81	0.32
KRU2012-03	0.83	0.97	0.81	0.75	0.84	0.67	0.65	0.84	0.31
KRU2012-06	0.85	0.96	0.82	0.75	0.81	0.68	0.66	0.84	0.32
KRU2012-07	0.83	0.97	0.80	0.74	0.83	0.67	0.66	0.85	0.32
KRU2012-10	0.84	0.97	0.83	0.73	0.82	0.68	0.64	0.83	0.31
KRU2012-11	0.84	0.97	0.82	0.74	0.82	0.67	0.65	0.83	0.32
KRU2012-13	0.86	0.98	0.84	0.74	0.83	0.69	0.65	0.84	0.32
KRU2012-16	0.86	0.97	0.84	0.74	0.81	0.69	0.65	0.83	0.32
KRU2012-17	0.84	0.97	0.83	0.74	0.82	0.68	0.65	0.83	0.32
KRU2012-18	0.84	0.96	0.82	0.73	0.82	0.68	0.64	0.83	0.32
LVP2013-01	0.85	0.98	0.83	0.74	0.83	0.68	0.65	0.84	0.31
LVP2013-02	0.85	0.97	0.84	0.74	0.81	0.68	0.65	0.82	0.32
LVP2013-03a	0.83	0.97	0.82	0.73	0.82	0.67	0.64	0.82	0.31
LVP2013-04	0.84	0.98	0.82	0.74	0.83	0.67	0.65	0.83	0.32
LVP2013-06	0.84	0.98	0.82	0.73	0.83	0.67	0.65	0.83	0.31

	Wakondo Tuff CAT09- 05 (.93)	Nyamita Tuff CAT09- 21 (.93)	Nyamsingula Tuff CAT10-03 (.89)	BTPT 'a' CAT11- 07a (.92)	BTPT 'b' CAT11- 07b (.85)	AV1004 T5A (.92)	CAT09- 02a (.93)	Songhor Tuff X-5A-3 (.93)	Rhyolitic Tuff LVP2013- 05 (.76)
LVP2013-07a	0.83	0.97	0.82	0.73	0.82	0.67	0.65	0.82	0.32
LVP2013-11	0.84	0.97	0.82	0.74	0.84	0.68	0.65	0.84	0.31
12KIS26	0.83	0.98	0.82	0.73	0.82	0.67	0.64	0.84	0.32
12KIS28	0.83	0.97	0.82	0.74	0.83	0.67	0.65	0.84	0.31
CAT10-03	0.86	0.82		0.75	0.70	0.74	0.70	0.71	0.40
CAT11-02b	0.85	0.77	0.91	0.79	0.70	0.78	0.74	0.71	0.40
DP10-16	0.88	0.83	0.97	0.74	0.71	0.73	0.69	0.73	0.40
DP10-17	0.86	0.82	0.98	0.74	0.70	0.72	0.69	0.72	0.41
DP10-18	0.87	0.82	0.96	0.74	0.70	0.73	0.69	0.72	0.40
LVP2013-3b	0.85	0.77	0.92	0.79	0.70	0.79	0.75	0.71	0.39
LVP2013-7b	0.84	0.78	0.93	0.79	0.69	0.78	0.74	0.70	0.40
LVP2013-8	0.87	0.79	0.92	0.81	0.71	0.79	0.75	0.72	0.39
LVP2013-13	0.89	0.84	0.95	0.74	0.72	0.73	0.70	0.74	0.39
12KIS34	0.85	0.79	0.94	0.79	0.70	0.77	0.73	0.71	0.40
CAT11-07a	0.82	0.75	0.75		0.68	0.78	0.81	0.86	0.34
CAT11-07b	0.75	0.83	0.71	0.68		0.62	0.60	0.78	0.28
CAT10-05a	0.82	0.75	0.75	0.98	0.69	0.78	0.80	0.86	0.34
CAT10-05b	0.77	0.83	0.71	0.70	0.97	0.62	0.62	0.80	0.28
LVP2013-09a	0.82	0.77	0.75	0.96	0.71	0.76	0.78	0.88	0.33
LVP2013-09b	0.77	0.83	0.71	0.69	0.97	0.62	0.61	0.79	0.28
LVP2014-10a	0.82	0.75	0.75	0.98	0.68	0.79	0.81	0.85	0.34
LVP2014-10b	0.76	0.84	0.72	0.69	0.97	0.62	0.60	0.79	0.28
LVP2014-14a	0.82	0.76	0.75	0.89	0.70	0.86	0.85	0.80	0.36
LVP2014-14b	0.76	0.86	0.74	0.69	0.94	0.62	0.60	0.79	0.29
LVP2013-15a	0.82	0.78	0.74	0.92	0.70	0.79	0.81	0.87	0.33
LVP2013-15b	0.74	0.84	0.72	0.66	0.94	0.60	0.58	0.76	0.28
AV1004T5A	0.81	0.68	0.74	0.78	0.62		0.91	0.70	0.41
CAT09-02a	0.76	0.66	0.70	0.81	0.60	0.91		0.73	0.41
X-5A-3	0.83	0.85	0.72	0.86	0.78	0.70	0.73		0.31
LVP2013-05	0.35	0.32	0.40	0.34	0.28	0.41	0.41	0.3	

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Table 4: Dose rate data, De values and pIRIR ages for the 2 samples from Nyamita and 3 samples from Wakondo.

Sample name	Moisture content		Dose rates (Gy/ka)			Total dose rate (Gy/ka)	De (Gy)	pIRIR age (ka)
	(%)	Beta	Gamma	Cosmic	Internal			
Nyamita RUP-1	11.5	1.73 ± 0.09	0.83 ± 0.04	0.18 ± 0.03	0.84 ± 0.07	3.57 ± 0.12	166 ± 11	46.4 ± 3.6
RUP-2	4.5	1.71 ± 0.08	1.01 ± 0.04	0.16 ± 0.02	0.84 ± 0.07	3.72 ± 0.11	185 ± 11	49.7 ± 3.5
Wakondo RUP-3	4.0	2.17 ± 0.10	1.37 ± 0.06	0.21 ± 0.03	0.84 ± 0.07	4.59 ± 0.14	38 ± 6	73.8 ± 6.3
RUP-4	5.7	2.18 ± 0.11	1.29 ± 0.06	0.21 ± 0.03	0.84 ± 0.07	4.46 ± 0.14	49 ± 7	67.5 ± 6.3
RUP-5	7.5	2.28 ± 0.12	1.41 ± 0.07	0.21 ± 0.03	0.84 ± 0.07	4.75 ± 0.16	23 ± 8	63.6 ± 6.0

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Table 5: Age estimates for tuffs discussed in this study.

Tuff	Minimum Age (ka)	Method	Maximum Age (ka)	Method
BTPT	35-42	¹⁴ C	49	Nyamita Tuff below +tephra correlations.
Nyamsingula	35-42	BTPT +tephra correlation	49	Nyamita Tuff +tephra correlations.
Nyamita	49	OSL	49	OSL
Nyamita Valley Trachytes	49	OSL of Nyamita Tuff + tephra correlations	94-111	U-Th
Rhyolitic tuff	49	OSL of Nyamita Tuff + tephra correlation	94-111?	presumed stratigraphic position above the Wakondo Tuff?
Wakondo	68	OSL	94-111	U-Th on tufa from Nyamita Valley.
Wakondo			100	Compositional similarity to Suswa phonolites.

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fig1

Fig 2

fig3

fig 4

fig5

fig6

fig7

Composite
tephro-
stratigraphy

BTPT

Nyamsingula
Tuff

Nyamita
Tuff

Nyamita
Valley
trachytic tuffs

rhyolitic tuff
(Kisaaka)

Wakondo
Tuff

Pleistocene tephra correlations of the eastern Lake Victoria Basin: Rusinga Island, Mfangano Island & Karungu, Kenya

Nyamsingula

DP10.14-
DP10.15

DP 10.18 DP 10.17 DP 10.16

Mfangano

Nyamita

AV 1001

14C 26-28 ka

AV 1002 AV 1003

14C 40 ka

OSL 46ka

OSL 50ka

Nyamita 2

Nyamita 3

Nyamita 1

AV 1006

U-Th= 94-111 ka

CRJ 2011

Wakondo West

Rat Hill

Wakondo

Bovid Hill OSL= 68 ka

Wakondo Tuff

Wakondo

Kisaaka

Kisaaka Main

KIS-10

ZTG

RCS

Kisaaka North

WPT 119 WPT 117

Sec. A

Aringo

WPT 101 WPT 096

Sample numbers of eastern Lake Victoria Basin

BTPT:

Mfangano: CAT10-05

Kisaaka: CAT11-07

Aoch Nyasaya: LVP2013-09, 10

Obware: LVP2013-14?, 15

Nyamsingula Tuff:

Nyamsingula: DP10-16,17,18

CAT10-03

Kisaaka: 12KIS-34

LVP2013-3b,7b,8

KRU2012-1,2,3

Unique Tuffs:

Kisaaka: LVP2013-05

Nyamita: CAT09-02a;

AV1004T5A

Nyamita Tuff:

Nyamita: AV1001T4,1002TA,

1003B2,1004T3C,

1004T4C,1006d

KRU2012-17,18;

CAT09-02b, 03, 04, 21

Kisaaka: CAT11-05;

KRU2012-10,11,13,16

LVP2013-1,2,4,6;

12KIS26, 28

Aringo: CAT11-01,02;

Obware: LVP2013-13

Aoch Nyasaya: KRU2012-6,7;

LVP2013-11

Wakondo Tuff:

Wakondo: CAT09-05;10-01

LVP2013-16

Nyamita: CAT09-01,22;

CRJ11-27,28;

AV1006B

Kisaaka: KRU2012-15

Obware

WPT

212-214

WPT

213

?

WPT

210

WPT

211

WPT

110

Aoch Nyasaya

WPT

211

WPT

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T. Faith

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fig10

fig11

fig12