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Paleoclimatic and paleoenvironmental framework of FLK North archaeological site, Olduvai Gorge, Tanzania

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ABSTRACT

The multi component FLK North archaeological site was discovered over 50 years ago, and its interpretation has been highly controversial since. Explanations of the dense bone and stone tool accumulation range from a site on a featureless lake margin that is dominantly anthropogenic in origin to a site near a freshwater wetland that is dominated by carnivore activity (e.g. felids and hyenas). FLK North occurs stratigraphically between the Ng'eju Tuff (1.818 ± 0.006 Ma) and Tuff IF (1.803 ± 0.002 Ma), and is composed of 9 distinct levels. Analysis of newly recovered fossil bones and artifacts has shown that the bones of large animals are largely the product of felid hunting and feeding behavior, followed by hyena gnawing and breakage of some bones. The expanded sample of felid prey remains is significant for understanding the contrasts between the mortality profiles of fossil assemblages produced by carnivores and those produced by hominins. Geologic mapping in the environs of the site has revealed rich sedimentological and paleoecological records and a thin, but persistent tuff (here named Kidogo Tuff) that is ~1.5 m below Tuff IF. Electron microprobe analyses of the tuff mineralogy revealed a unique geochemical fingerprint that permits its use for correlation of widely separated outcrops and facilitates the high resolution reconstruction of the landscape at the time of site formation. The 9 archaeological levels comprise a relatively continuous record through a Milankovitch precession cycle (dry-wet-dry). As the lake receded into the central basin during the dry part of the cycle, surface water supplies dwindled and groundwater-fed springs and wetlands became the dominant freshwater supply. The FLK North archaeological record essentially ended when level 1 was covered with 0.4 m of Tuff IF in a violent volcanic eruption of nearby Mt. Olmoti. However, the overlying Bed II sediments contain scattered archaeological material and a freshwater carbonate deposit that is similar to those found associated with other Bed II archaeological sites, e.g. VEK, HWK and HWKE. The recognition of the ecological association of springs, wetlands and archaeological remains is a powerful predictive tool for locating new archaeological sites in this region that is known for hominin remains.

1. Introduction

Olduvai Gorge, northern Tanzania, was created in the late Pleistocene by river incision into a shallow basin of volcaniclastic sediments on the margin of the East African Rift System (EARS) (Fig. 1, inset) (Hay, 1976). Outcrops along the gorge expose a two-million-year-long record of flora and fauna including nearly 100 hominin fossils (Fig. 2a). Over fifty years ago Louis and Mary Leakey drew the world's attention to Olduvai with the discovery of two hominin species, *Paranthropus* and *Homo habilis* (Leakey, 1971). Although there are over 250 km^2 of fluvial and lacustrine deposits exposed in the basin, most of the archaeologically productive sites

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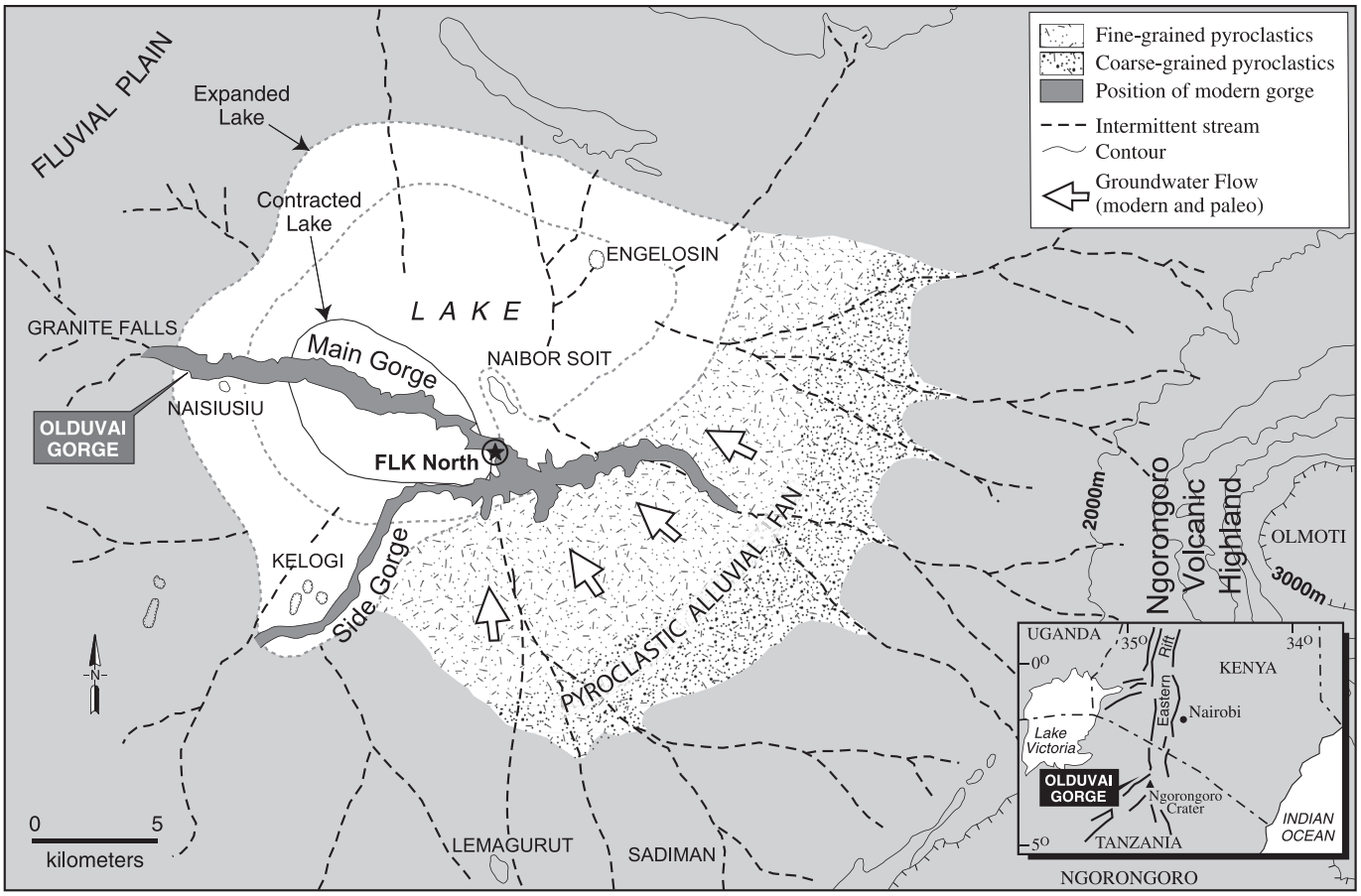

Fig. 1. Location maps. Inset map provides the regional context of Olduvai Gorge (3° S, 35° E) on the west margin of the East Africa Rift System in northern Tanzania. Paleogeographic reconstruction of Olduvai Basin (~1.85–1.75 Ma) shows location of paleo Lake Olduvai and the area covered during expanded and contracted phases (modified from Hay, 1976). FLK North archaeological site is near the junction of the main and side gorges. Ngorongoro Volcanic Highland (3000 m high) lies to the east and south creating a prominent rain shadow for the basin. Precipitation trapped by the Highlands infiltrates and flows into the basin (arrows represent the direction of modern and paleo groundwater flow).

are found in a relatively small area (7 km^2) centered on the junction of the Main and Side Gorges (Fig.1). Paleogeographic reconstruction of the Olduvai basin by Hay (1976) places a shallow lake in the center of this area with a broad, gently-sloping lake margin flat encircling the lake. The area of concentrated tools and fossils is within the lake margin zone. The initial assumption was that the concentration of archaeological material was somehow linked to the lake (Leakey, 1971; Hay, 1976). Subsequent studies of the paleoenvironment revealed that paleo Lake Olduvai was saline-alkaline (Hay and Kyser, 2001; Hover and Ashley, 2003; Deocampo et al., 2009) and thus unlikely a source of freshwater for animals, including humans. The lake was a playa and fluctuated on both short time scales (hundreds of years) (Liutkus et al., 2005) and long term Milankovitch precession cycles (~21–23,000 years) (Ashley and Driese, 2000; Ashley, 2007; Magill et al., 2012a,b).

One of the first sites to be discovered in the Gorge was FLK North (Leakey, 1971) (Fig. 1). Discovered in 1959, excavations began the next year and revealed a puzzling mix of stone tools, large mammal skeletons, carnivore-ravaged bones, copious micro-mammal remains and carnivore dung. Artifact analysis by Leakey (1971) and re-analyses of her published data or specimens by others (Bunn, 1982; Potts, 1988; Egeland, 2008) continued to fuel the controversy regarding the origin of the site. Was site formation dominantly anthropogenic involving the butchering of animals obtained through scavenging and/or hunting, or, was the site produced by carnivore predation and feeding activity, or a combination of both? Were there tool-carrying hominins and carnivores at the site at the same or different times?

The FLK North archaeological material is found within 9 distinct levels in a "time slice" between two tuffs, Ng'eju Tuff and Tuff IF (Fig. 2b). Investigations initiated in 2007 by TOPPP (The Olduvai Paleoanthropology and Paleoecology Project) yielded geological and botanical data concerning the paleoenvironmental context of FLK North. These data indicate that the site was in a groundwater-fed palm forest/woodland or bushland (Barboni et al., 2010) with widespread freshwater wetlands nearby (Ashley et al., 2010a). Recent excavation of levels 1 and 2 have yielded several hundred stone artifacts and >2000 large mammal fossils that show minimal evidence of butchery by hominins and abundant evidence of carnivore and rodent gnawing. These new data support the idea that hominins played a minor role in site formation, contrasted to the dominant role of carnivores (Domínguez-Rodrigo and Barba, 2007; Bunn et al., 2010).

The evolving behavioral reconstruction suggests that felids brought prey animals to the site and hyenas scavenged from abandoned felid meals. Presumably at different times hominins butchered several large ungulates and discarded artifacts (Bunn et al., 2010). To develop the working hypotheses further, a much higher-resolution physical reconstruction of the site and its environs is needed for both temporal and spatial scales. The 9 archaeological levels span ~15–22,000 years (a complete or nearly complete Milankovitch wet-dry climate cycle) and yet the

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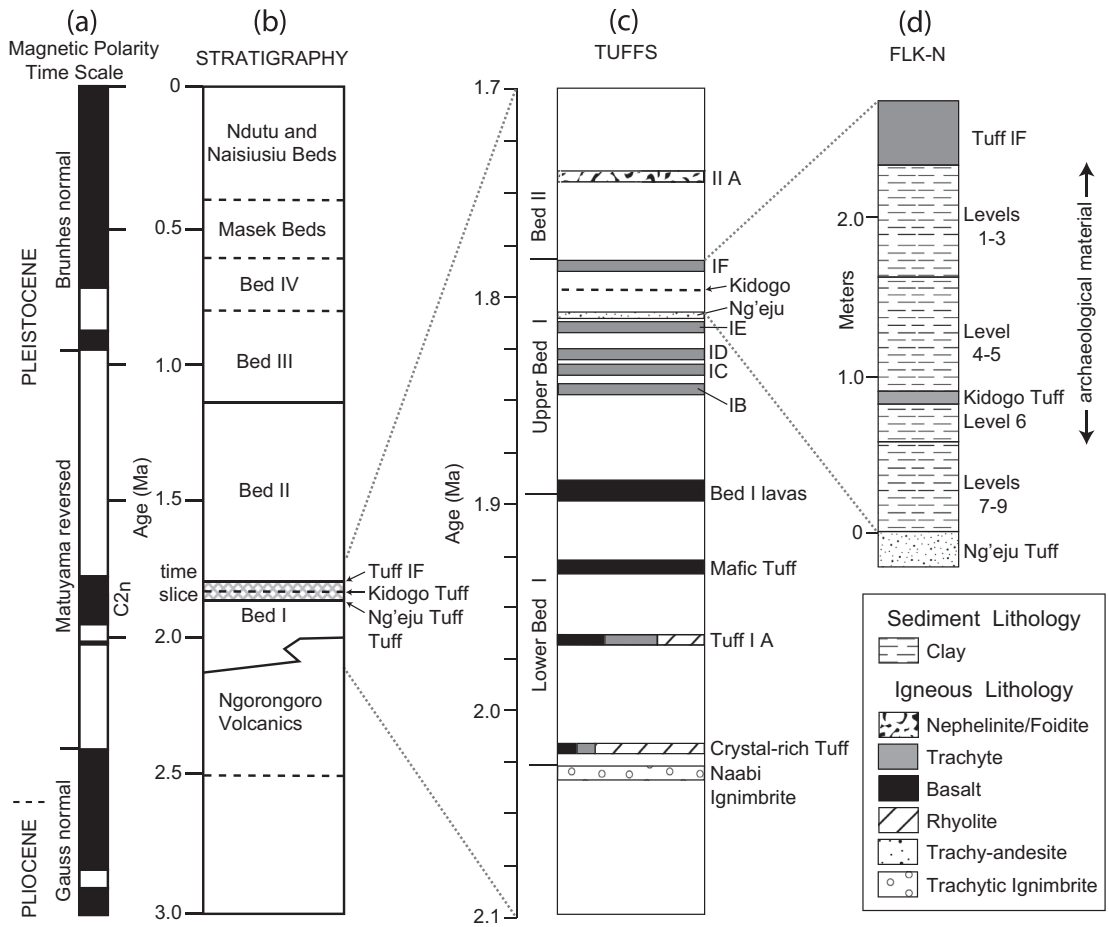

Fig. 2. Geologic column. **(a)** Magnetic polarity time scale (Hay, 1976). **(b)** Stratigraphy of Olduvai Gorge with the time slice of the FLK North archaeological site indicated (modified from Hay, 1976). **(c)** The tuff sequence of Bed I and Lowermost Bed II shows the variation in composition (modified after McHenry et al., 2008). These differences can be used for correlation among sedimentary sequences in the Gorge. **(d)** High-resolution stratigraphic section of FLK North reveals a 3 m section composed of repetitious waxy clay beds intercalated with tuffs. The sediments in which archaeological material are known to occur are indicated. The Kidogo Tuff is used in this study for correlation among outcrops in the environs of the site.

environmental conditions were previously time-averaged over this period (Fernandez-Jalvo et al., 1998; Egeland, 2008; Ashley et al., 2010a). The topography and vegetation cover were also "space and time averaged" over this same period largely because of the inability to correlate among widely separated outcrops. In order to develop realistic behavioral models, a more precise, as well as a realistic reconstruction of the site and environmental changes through time is needed.

1.1. Objectives

The objectives of the paper are to:

(1) Describe a newly identified tuff, its geochemical fingerprint and its position within the Olduvai tuff sequence established by Hay (1976), McHenry (2005) and Deino (2012). Characterization of this tuff will facilitate correlation among outcrops.
(2) Develop a high-resolution reconstruction of the landscape in the environs (0.5 km^2) of FLK North using sedimentary facies and stable isotope geochemistry of carbonates. The recognition of the ecological association of springs, wetlands and archaeological remains has the potential of being a powerful predictive tool for locating new archaeological sites.
(3) Report on the new sample of archaeological material recovered at the site since 2010.
(4) Construct the long term paleoenvironmental history of the site based on stratigraphy exposed in recent excavations to provide a paleoclimatic and paleoenvironmental background against which short-term data sets from the levels can be compared.

2. Background

2.1. Geology

Olduvai Gorge is an incised river system draining eastward toward the Ngorongoro Volcanic Highlands; the Gorge dissects a sedimentary basin on the margin of the East African Rift System. The Eastern Rift extends over 5000 km from the Suez to Lake Malawi cutting through continental crust on the eastern side of Africa (Fig. 1 inset). The rift is expressed topographically as a single elongate 100–150 km wide valley segmented along its length into rift basins (Dawson, 2008). In northern Tanzania the rift splits into two distinct rift valleys separated by a large volcanic complex, the Ngorongoro Volcanic Highland or Crater Highlands, composed of a number of volcanoes that have been active in the region for over 5 million years (Dawson, 2008; Mollel et al., 2011; Deino, 2012). The Olduvai sedimentary basin was formed at ~2.0 Ma. When formed, the basin was an estimated 3500 km^2 in area and roughly circular, ~50 km wide and shallow (100 m) (Ashley and Hay, 2002). The sedimentary record preserved in the basin center is 30 km in

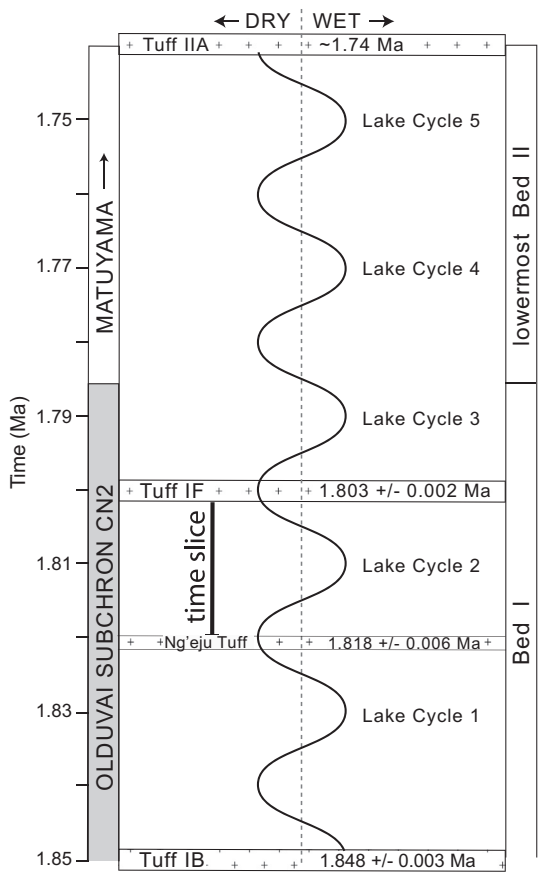

Fig. 3. Lake cycles. The wet-dry cycles of climate that have been documented by both lithology (Ashley, 2007) and isotopic studies (Magill et al., 2012a,b) are shown between Tuff IB and Tuff 11A. The time slice of the FLK North archaeological site occurs during Lake Cycle 2 between Ng'eju Tuff and Tuff IF. Dates are from Deino (2012).

diameter (Fig. 1) and contains a sedimentary record that archives a rich faunal and cultural record of early hominins. It also contains an important record of the biological and behavioral evolution of early humans. The basin has a number of well-dated tuffs that allow basin-wide correlation of widely separated outcrops, as well as dating of archaeological sites (Blumenschine et al., 2003; McHenry, 2005; Deino, 2012). Hay's (1976) reconstruction of Olduvai basin indicated a closed depression which gradually filled with air-fall tuffs, lava flows and reworked volcaniclastic sediment from the Ngorongoro Volcanic Highland to the east and fluvial sediments washed in from the Serengeti Plains that lie to the west.

2.2. Climate, paleoclimate and Hydrology

Precipitation in this region varies seasonally with location, topography and on the long term with astronomically controlled (Milankovitch) climate cycles (Trauth et al., 2007). Estimates of paleo precipitation in the Gorge vary from 250 mm/y during Milankovitch dry periods to 700 mm/y during wet periods (Magill et al., 2012b). The physical record of the climate cycles are a cyclic record of lake sediments (Ashley, 2007). Their record through time is depicted in Fig. 3. The modern mean annual temperature (MAT) averages 25 °C and the potential evapotranspiration (PET) estimated at ~2000–2500 mm/y is 4 times the precipitation resulting in a negative hydrologic budget for the year (Dagg et al., 1970). Olduvai is located near the equator and thus the MAT did not likely fluctuate much in the past, even though the rainfall did. Few, if any,

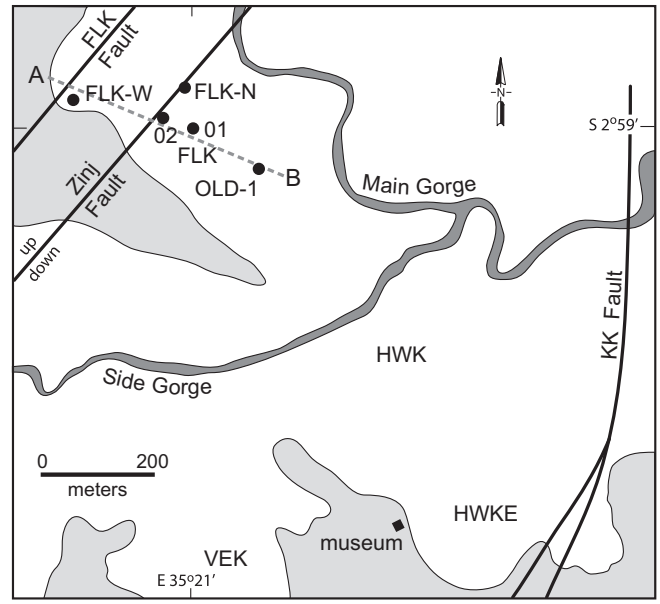

Fig. 4. Section location map. The map shows the relative position of the FLK North archaeological site (FLK-N) and the geologic sections used in the research. The study is centered in the "junction" area, the confluence of the Main and Side Gorges. The transect line A–B for Figs. 6 and 10, three faults and other archaeologically rich areas (HWK, HWKE, and VEK) from Leakey (1971) are also shown.

perennial rivers can persist with this highly negative water budget, and thus most rivers draining into the basin are considered intermittent and ephemeral (Hay, 1976; Ashley and Hay, 2002).

The modern Ngorongoro Volcanic Highland (to the east of the gorge) is over 3000 m high. It traps moisture-laden easterly winds blowing from the Arabian Sea and creates a rain shadow to its west. The modern rainfall on Ngorongoro is 1150 mm/y (Deocampo, 2004) and could have been twice that during Milankovitch wet periods. Some rainfall runs off in ephemeral surface streams, but most infiltrates into the relatively porous volcaniclastic deposits of the Highlands and moves westward in the subsurface into the Olduvai Basin (Fig. 1). Today groundwater exits at the base of the slope contributing to the lake/swamp called Obalbal. Obalbal is a sump collecting groundwater flowing from the Highlands to the east and seasonal run-off from the modern Olduvai River flowing from the west. The hydrogeologic setting was likely similar in the past (Fig. 1). We know that groundwater discharge into the basin was important to animals (including hominins) in the past. High-resolution studies of paleoclimate and paleoenvironmental reconstruction have revealed a number of springs and wetlands associated with archaeological sites in the Olduvai Basin, Middle Bed 1 (Ashley et al., 2010b), Upper Bed I (Ashley et al., 2010a) and Lowermost Bed II (Liutkus and Ashley, 2003; Ashley et al., 2009; Deocampo and Tactikos, 2010).

3. Methods

3.1. Field

The area of study is FLK North, originally named by Mary Leakey (Leakey, 1971) and described as Loc 45a by Richard Hay (Hay, 1976). Stratigraphic sections (FLK-01, etc.) are geological step trenches (1–2 m wide and 2–3 m high). The stratigraphy was described, logged using scaled drawings, and photographed. Representative samples were collected for analyses and site locations documented using global-positioning-satellite methods (GPS). Fig. 4 shows the location of the sites relative to each other.

Fig. 5. Bed I outcrop. A photo taken in 1960 of the freshly dug FLK Zinj excavation (located 100 m south of FLK North) clearly shows the tuff sequence of the study time slice, Ng'eju Tuff, Kidogo Tuff and Tuff IF at the top of Bed I (Photo by R.L. Hay).

Annual excavation by TOPPP began in 2007 and expanded Leakey's excavation to the southeast into the FLK North ridge. The locations of all stone artifacts and fossils greater than 2 cm in length are recorded with a laser transit and artifacts and fossils are drawn to scale. Long-axis orientations of elongate pieces and their dip are recorded using a Brunton compass. Smaller pieces are recovered through fine mesh screening of all excavated sediment. New excavation trenches have exposed more than 50 square meters of the surface of level 1 underneath Tuff IF, which immediately overlies Bed I (Fig. 2b).

3.2. Laboratory

3.2.1. Tuff analysis

Feldspar fragments from μm to mm in size were analyzed. The selected grains were embedded in a 25 mm diameter epoxy resin butt and prepared for analysis. Samples were analyzed for eight elements using the electron microprobe (JEOL: JXA-8200), operated at 15 kV and 5–15 nA beam current. The X-ray intensities from the tuff samples were quantified using established procedures and calibrated against a suite of thirteen internationally traceable microanalytical standards (Jarosewich et al., 1980). These results were used as either weight percent of the oxides or molecular ratios. ZAF correction procedures based on the John Donovan "Probe for EPMA" software package were applied.

3.2.2. Carbonate analysis

Carbonate samples weighing 550 μg–900 μg were ground to fine powder. The $\delta^{13}C$ and $\delta^{18}O$ values of carbonate samples were analyzed at Rutgers University in the Stable Isotope Laboratory in the Department of Earth and Planetary Sciences. Samples were loaded into a Multiprep device attached to a Micromass Optima mass spectrometer. The CaCO3 was reacted in 100% phosphoric acid at 90 °C for 800 s. Values are reported in standard per mil (‰) notation relative to the Vienna Pee Dee Belemnite standard (V-PDB) through the analysis of an internal laboratory standard that is routinely measured with NBS-19 calcite. We use the Coplen et al. reported values of 1.95 and −2.20‰ for $\delta^{13}C$ and $\delta^{18}O$, respectively (Coplen et al., 1983). The long-term standard deviations on the internal lab standard are 0.05 and 0.08‰ for $\delta^{13}C$ and $\delta^{18}O$, respectively.

4. Results

4.1. Stratigraphy

4.1.1. Upper Bed I

Upper Bed I stratigraphy is a 'layer cake' of interbedded tuffs and fine-grained sediment (Fig. 5). The dominant lithology, in which the archaeological material is found, is monotonous clay with minor amounts of silt and essentially no sand or gravel (Fig. 6). The 2–3 m thick record is composed of numerous vertically stacked sedimentary units that have been pedogenically modified, with colors that vary from olive to grayish brown (Munsell, 2000) These clay-rich paleosols are paleo-vertisols and include soil features such as peds, slickensides, carbonate-filled root traces and carbonate nodules (Southard et al., 2011; Beverly, 2012; Beverly et al., 2013). Outcrops surrounding FLK North contain carbonate beds that range in thickness from 10 cm (FLK-W) to a 1.4 m thick tufa mound (FLK-02). The carbonates are light colored (white to tan) calcite, with highly porous, chalky texture. Root casts, clay blebs and rare ostracods shells also occur.

Sediments are in a "time slice" sandwiched between two tuffs, Ng'eju Tuff (1.818 ± 0.006 Ma) and Tuff IF (1.803 ± 0.002 Ma) (Fig. 2d). There are also a number of intercalated tuff beds that range in thickness from 50 cm (FLK-02) to <1 cm thick. One tuff deposit (8–10 cm thick) in the midst of a meter of clay was visually distinctive and laterally persistent. This tuff is found in all sections except FLK-W where it may be in the subsurface, as the lower portion of the "time slice" is not exposed. The thin tuff, here named Kidogo Tuff is visible in outcrop (Fig. 5) and has a distinctive mineralogy, described below, that facilitates stratigraphic correlation (Fig. 7).

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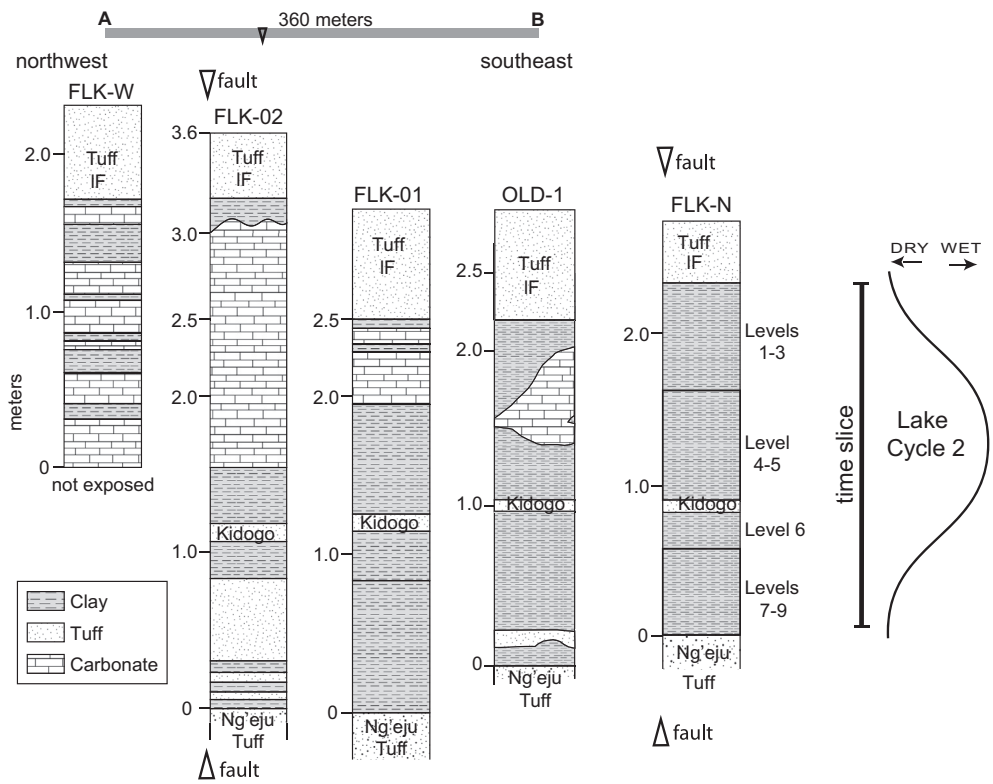

Fig. 6. Fence diagram. Four stratigraphic sections (2–3 m high) from the time slice reveal lithologically similar records of waxy clay and carbonate sandwiched between Ng'eju Tuff and Tuff IF. The Kidogo Tuff is exposed in all sections except FLK-W and can be used to correlate with the levels at FLK North which lies ~100 m north of the A–B transect.

4.1.2. Tuff IF

Tuff IF is the uppermost deposit of Bed I (Figs. 2, 6 and 8). It was used by Hay (1976) as a stratigraphic marker bed for correlation throughout the Olduvai basin. Tuff IF has a silica-undersaturated trachytic to phonolitic composition and it was sourced from eruptions of the Mt. Olmoti volcano (Fig. 1). The tuff has been studied by Hay (1976), McHenry (2005) and Stollhofen et al. (2008), and dated by Deino (Blumenschine et al., 2003; Deino, 2012). Where complete, the tuff has laminated volcanic surge deposits at the base overlain with reworked pumice deposits, eolian and fluvial

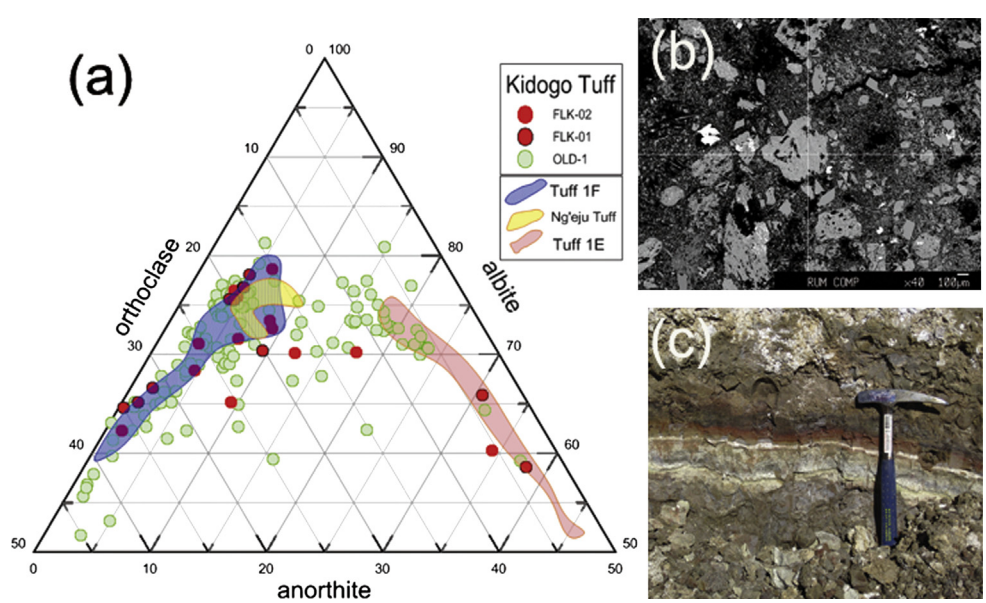

Fig. 7. Feldspar in tephra. **(a)** Feldspar ternary diagram (anorthite-albite-orthoclase) for Kidogo Tuff at three localities (FLK-01, FLK-02, OLD-1) and three associated tuffs: Tuff IE and Ng'eju Tuff below and Tuff IF above (Fig. 2c). Compositional ranges are shown as fields for the three tuffs. **(b)** Backscattered electron micrograph of Kidogo Tuff showing abundant feldspar clasts (light gray) embedded in siliceous matrix (dark gray). **(c)** Exposure of 9 cm thick Kidogo Tuff at OLD-1. Tuff is capped with a dark brown/red paleosol rich in Fe and Mn that formed when groundwater flow was inhibited by the tuff.

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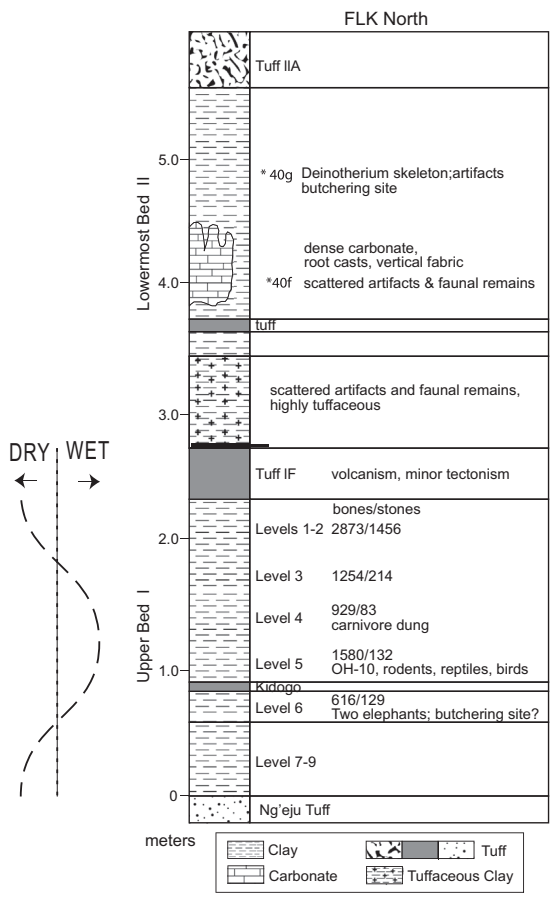

Fig. 8. Summary of FLK North. The archaeological site represents a 15–22,000 year long history of bone and stone tool accumulation at the top of Bed I during Lake Cycle 2. Following the catastrophic volcanism of Tuff IF the archaeological record is relatively sparse. A tantalizing dense carbonate deposit was uncovered just above the current excavations of FLK North indicating that freshwater was available well into Lowermost Bed II. Archaeological data (descriptions and numbers of bones/stones) are from Egeland (2008) and Leakey (1971).

deposits. The FLK North area was blanketed with Tuff IF as an airfall deposit filling in lows on the topography and thinner over highs. FLK-N, a topographic "high" received only 40 cm, whereas FLK-W (60 cm), FLK-02 (60 cm), FLK-01 (70 cm), and OLD-1 (75 cm), all in topographic lows, received more (Fig. 4). When the eruption occurred, the landscape was completely covered by ash and artifacts on the surface were quickly buried and preserved. The ecological impact of the multi episode deposition of Tuff IF was estimated to have lasted 2–3 thousand years (Stollhofen et al., 2008).

4.1.3. Lowermost Bed II

Excavations at FLK North have exposed ~3 m of section above Tuff IF (Fig. 8). A reconnaissance-level study of the geology was carried out. Shallow depressions (animal trails?) were sculpted into the top of Tuff IF (Leakey, 1971) and in a few places Tuff IF was completely removed (see Leakey, 1971, Fig. 31). These shallow depressions were ultimately filled in with waxy clay and reworked tuff (probably Tuff IF) as the lake level rose during a reversal to wetter climate, Lake Cycle 3, in Lowermost Bed II time (Fig. 3). A 70 cm thick dense carbonate bed that is laterally persistent occurs about 1.2 m above Tuff IF (Figs. 8 and 9). The carbonate has abundant organo-sedimentary structures, such as openwork fabric, abundant root casts, root tubules, and nodules (Klappa, 1980). The morphology and texture suggests that the carbonate formed subaerially from groundwater discharging on dry land (not submerged under lake water) (Guido and Campbell, 2012). The carbonate thus formed on the lake margin flat during a time of lower lake level. The spring water was likely sourced from groundwater flowing from the Zinj Fault system (Fig.10). Archeological material was noted in Lowermost Bed II by M. D. Leakey, but not excavated (Leakey, 1971). The reports of the archaeological material sound promising. Fig. 8 depicts the stratigraphic position of scattered artifacts and faunal remains (archaeological site 40f) that occurs ~1.4 m above Tuff IF. A second, younger archaeological site (40 g) is 2 m above Tuff IF. It is a *Deinotherium* skeleton which she interpreted as a butchering site (Leakey, 1971).

4.2. Archaeology

Expanding the excavation of FLK-N beyond Mary Leakey's original excavation of the site in the early 1960's has two objectives.

Fig. 9. Lowermost Bed II. A 70 cm thick dense carbonate bed occurs 1.2 m above Tuff IF and appears to have been derived from groundwater flowing from the Zinj Fault system that passes through the archaeological site.

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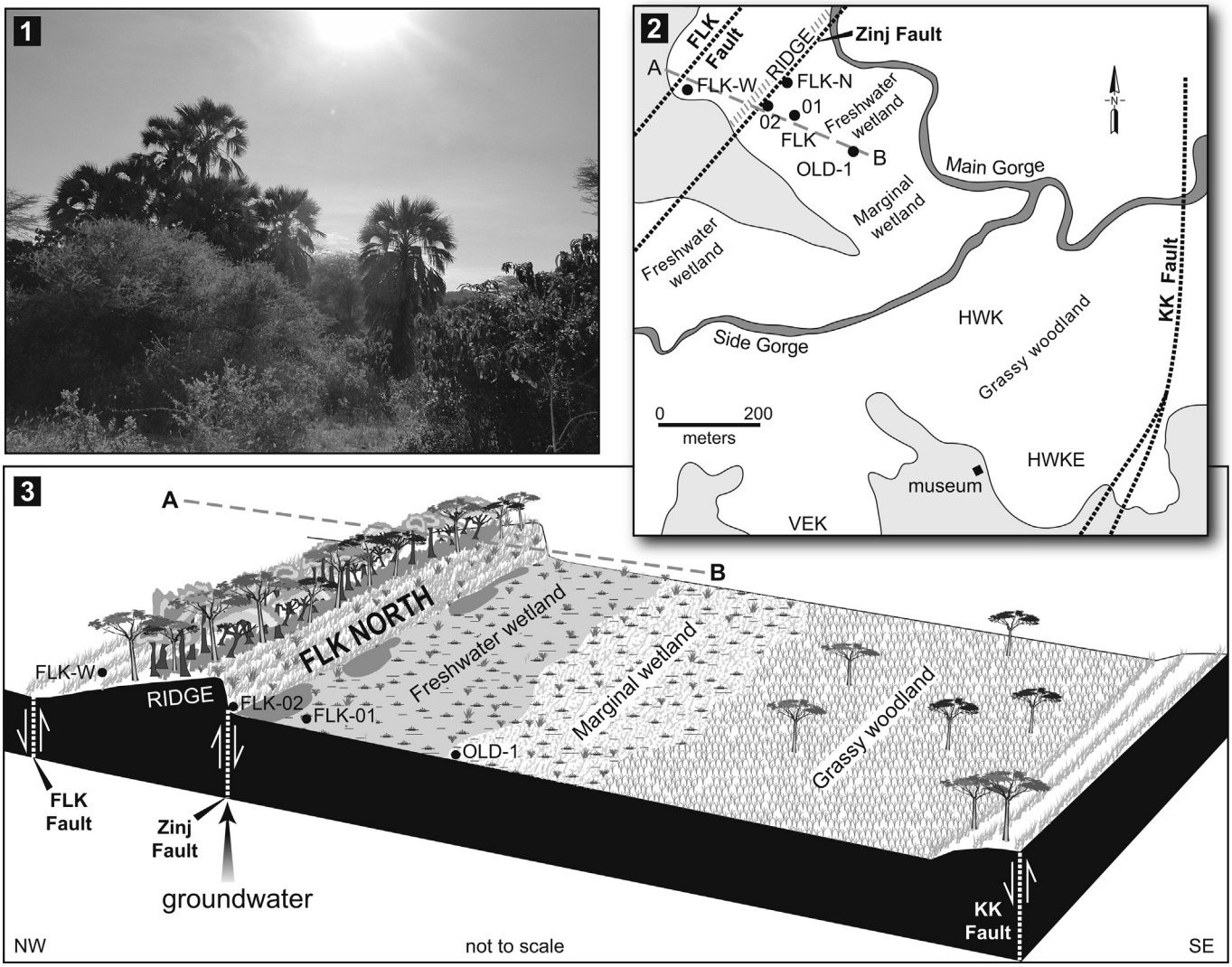

Fig. 10. Paleoecology of FLK North. **1**. Photograph of a groundwater-fed palm and acacia woodland in Manyara National Park, Tanzania. **2**. Map of the samples sites, fault and the FLK North Ridge. Transect line A–B is shown on the block diagram in C. **3**. A diagrammatic reconstruction of the landscape in the environs of the FLK North based on the lithology and carbonate isotopes (this study) and paleobotanical data from Barboni et al. (2010). The site was on a wooded topographic high (uplifted side of the Zinj Fault) with a groundwater-fed spring, sourced from the fault. Small pools occurred within freshwater wetlands that changed to more open woods and grassland cover to the south (VEK) and southeast (HWK and HWKE).

First, to obtain a new sample of fossils and artifacts using current methods, and to facilitate a new analysis of the taphonomic history of the site; second, to place the archaeological components on the site within the context of paleoenvironmental landscape, as well as establish the horizontal extent of the site within that context.

Recent excavation strategy has sought to define the horizontal limits of the site by expanding the excavation to the southwest and to the northeast of Leakey's original trenches. This work has established that the density of remains in the levels 1 and 2 immediately below Tuff IF decreases to the southwest. To the northeast, the conditions of site formation remain ill defined. Provisionally, Tuff IF and underlying levels 1 and 2 (all in Bed I) have been removed by erosion. An erosional unconformity is visible at the northeast end of our excavation. Immediately above the unconformity, a Bed II archaeological level incorporates small fist-sized lumps of Tuff IF and exhibits a preferred orientation of elongate, current-sensitive bones. Below it, we can correlate with the stratigraphy of level 3 (Bed I) and underlying levels known from the central and southwestern areas of the site.

Analysis of the newly recovered fossil bones and artifacts show that the bones of large animals are largely the product of felid hunting and feeding behavior, followed by hyena gnawing and breakage of some bones (Bunn et al., 2010). The expanded sample of felid prey is significant for understanding the contrasts between the mortality profiles of fossil assemblages produced by carnivores and those produced by hominins. Reanalysis of the stone artifacts at this site demonstrates that they are designed for battering activities more than for producing sharp-edged flakes for butchery or other cutting or scraping activities (Diez-Martín et al., 2010). These results are consistent with a recent reanalysis of the Leakey collections from the site by Domínguez-Rodrigo and Barba (2007).

4.3. Tephra correlation

Geologic mapping in the environs of the site has revealed a thin, but persistent tuff (here named Kidogo Tuff – Kiswahili for "small") ~1–2 m below Tuff IF. This thin pyroclastic unit, up to 10 cm thick, occurs in all complete exposures in the FLK North area (Fig. 6) and is

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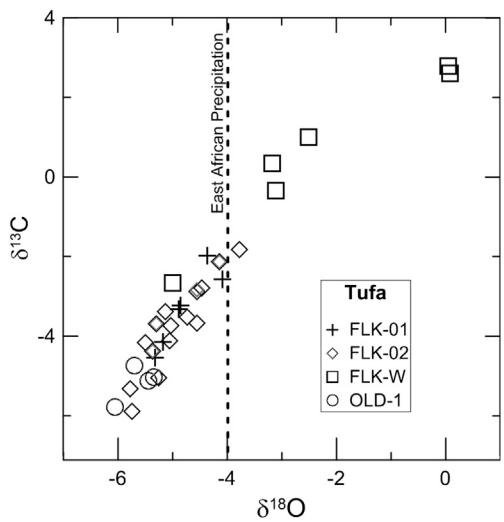

Fig. 11. Stable isotope plot. Bivariant plot of stable isotopes of O and C of carbonates from the stratigraphic sections (Fig. 6). The $\delta^{18}O$ ratios of FLK-01, FLK-02 and OLD-1 are tightly clustered between −6‰ and −4‰ and the $\delta^{13}C$ values between −5‰ and −2‰ showing a very clear freshwater signal. The value of the meteoric $\delta^{18}O$ in the region (−4‰) is indicated. The isotope ratios of the carbonate FLK W, to the west, are clearly different (more positive) indicating a different fractionation history during deposition. The carbonate at OLD-1 is freshest of all.

well positioned to facilitate the high-resolution reconstruction of the landscape during the time of site formation. The Kidogo Tuff is sandwiched between the Ng'eju Tuff, below, and Tuff IF, above (Fig. 2). The tuff contains light gray tephra that are dominantly felsic and clast sizes range from 5 to 10 μm to greater than 100 μm. Electron microprobe analyses of the tuff mineralogy revealed a unique geochemical fingerprint that allows for correlation of widely separated outcrops over about a 0.5 km^2 area (Baluyot, 2011). Specifically, the variable compositions of feldspar minerals, i.e. their calcium (anorthite), sodium (albite) and potassium (orthoclase) contents can be used to constrain their origins. The feldspar in the Kidogo Tuff ranges from plagioclase ($Ab_{58}Or_4$) through anorthoclase ($Ab_{75}Or_{10}$) to K-rich ($Ab_{51}Or_{45}$) in contrast to the limited compositions ranges of the adjacent Ng'eju Tuff ($Ab_{75}Or_{20}$ ±5) and Tuff IF ($Ab_{77\text{-}60}Or_{20-40}$).

The use of tephra for correlation is based on the concept that the composition of the felsic clasts in the tephra reflects the composition of the volcanic source. At Olduvai, the variation of tephra compositions echoes the changes caused by evolution of the volcanoes through time. Between Bed I and Bed II times the tuffs become more alkalic (McHenry et al., 2008) and the Kidogo Tuff straddles this transition (Fig. 2c). Its wide feldspar compositional range reflects this evolutionary transition in the magma chamber and provides the Kidogo Tuff with a distinctive chemical fingerprint. It differs from tuffs below and above (Fig. 7). The compositional range of feldspars in the Kidogo Tuff is consistent with the transition from Bed I volcanics to the more alkaline volcanic sequences of Bed II (usually considered to begin with the later Tuff IF) (Fig. 2c).

4.4. Carbonate geochemistry

Stable isotope geochemistry has been found to be useful in paleoenvironmental and paleoclimatic reconstruction in continental settings (Alonso-Zara and Wright, 2010). Oxygen isotope signatures of freshwater carbonate reflect the effects of both the starting ratio in the rainfall to the area and subsequent fractionation due to evaporation. The $\delta^{18}O$ of meteoric water reaching the tropical East Africa is −4.0‰ supporting the interpretation that the carbonates are sourced by precipitation (deMenocal et al., 2000) (Fig. 11). Atmospheric $\delta^{13}C$ is −6‰ (pre-industrial atmosphere) (Cerling and Hay, 1986). Carbon values in the carbonate, however reflect both the initial value from the atmosphere and the effects of biological fractionation by C3 and C4 plants and animals in the soil zone. Fig. 11 depicts the isotope signature of carbonates samples from four sections surrounding the archaeological site (Fig. 6). The spectrum of oxygen ratios reflects the fractionation due to evaporation (Benson et al., 1996; Liutkus et al., 2005). The value of the meteoric $\delta^{18}O$ in the region (−4‰) is indicated. The $\delta^{18}O$ ratios of FLK-01, FLK-02 and OLD-1 are tightly clustered between −6‰ and −4‰ and the $\delta^{13}C$ values between −5‰ and −2‰ showing a very clear freshwater signal. The isotope ratios of the intercalated carbonate deposits at FLK-W, to the west, are clearly different (more positive) indicating a different fractionation history (more evaporation) during deposition. Carbonates in the Olduvai basin have a distinct stable isotope signature separate from calcium-rich soils (Cerling and Hay, 1986; Sikes and Ashley, 2007) and lake sediments from the same basin (Hay and Kyser, 2001; Sikes and Ashley, 2007).

5. Discussion

5.1. Depositional environments

The geological record of the FLK North archaeological site is stratigraphically located between Ng'eju Tuff and Tuff IF and is composed primarily of magnesium-rich smectitic clays (named "waxy" clays by Hay, 1976). There are no limestones, as such, at the archaeological site but carbonate root fillings nodules and concretions are present (Fig. 8). The sediments are well mixed, likely bioturbated by plants and vertebrates (Ashley and Liutkus, 2002; Barboni et al., 2010). The Kidogo Tuff is present, but other tuffs were not observed and may well have been mixed into the sediments. The archaeological site appears to be situated on a low relief ridge, the uplifted (hanging wall) side of the Zinj Fault (Ashley et al., 2010a) (Fig. 10). The site was slightly higher than the surrounding terrain on the broad lake margin, but low enough to be periodically flooded (covered) by lake water (and sediment). Lake expansion occurred frequently during Milankovitch wet periods (Fig. 3), and even during drier times monsoon-driven seasonal lake flooding could occur (Liutkus et al., 2005). The clay deposits are seen as an amalgamation of hundreds to thousands of short and long term lake expansion events; each expansion depositing a thin veneer of sediment. Sedimentation rate of non-tuff sediments in Bed I and Lowermost Bed II has been calculated to be ~0.1 mm/y (Hay, 1976; Ashley, 2007; Magill et al., 2012a). This estimate suggests that the time period between Ng'eju Tuff and Tuff IF could be 22,000 years long (within the error of the ^{40}Ar–^{39}Ar tuff dates). The time between Kidogo Tuff and Tuff IF (levels 1–5) could be as much as 15,000 years.

Phytolith and pollen data indicate that the low ridge supported a woodland with palm trees (Barboni et al., 2010), with the exact location of the site caused by geologic factors related to the Zinj Fault. The "Zinj Fault" was newly identified in Ashley et al. (2010a) (their Fig. 4), and is an extension of an unnamed normal fault mapped in the Side Gorge (near Loc 88a in Hay's Fig. 3) (Hay, 1976). The Zinj Fault runs northeast-southwest parallel to the FLK Fault, but lies ~150 m to the east. The up-thrown side (the hanging wall) of the fault created a low ridge (+1 m) that was well drained enough to support trees (Fig. 10). This geologically-controlled setting ensured the longevity of the landscape and allowed the repeated use of the area by carnivores and hominins likely leading to its palimpsest character (Bunn et al., 2010; Domínguez-Rodrigo et al., 2010).

The FLK-02 tufa mound (1.4 m thick) located ~75 m southwest from the archaeological site (FLK-N) is immediately adjacent to the fault (or fracture zone), but on the down-dropped (footwall) side (Fig. 4). The source of the carbonate at FLK-02 appears to be the groundwater flowing from the fault itself based on the $\delta^{18}O$ stable isotope values, −5.78‰ to −3.78‰ (Baluyot, 2011; Beverly, 2012) (Fig. 11). Water temperatures in modern regional freshwater marshes range from 20° to 28 °C (Deocampo, 2001), and modern regional rainfall has an average $\delta^{18}O$ (relative to VSMOW [Vienna standard mean ocean water]) value of −4.0‰ (Cerling and Quade, 1993). Calcite precipitated under these conditions will have $\delta^{18}O$ (V-PDB) values of ~−6‰. The carbonate precipitated from the water at FLK-02 indicates little evaporation and was very fresh indeed. FLK-01 which is located further (~75 m) from the fault has a $\delta^{18}O$ stable isotope signal (−5.3‰ to −2.0‰) that is slightly more fractionated (thus indicating more evaporation). Botanical studies of phytoliths and pollen from sediments near FLK-01concluded that the area surrounding FLK North was locally densely wooded at the time of deposition of Tuff 1F (Barboni et al., 2010).

OLD-1, which is furthest away (250 m), is even "fresher" than FLK-02. The $\delta^{18}O$ values are (−6.0‰ to 5.34‰) indicating rapid precipitation of carbonate, in equilibrium with the atmosphere (Gonfiantini et al., 1968). There is no field evidence of a fault at OLD-1, although there may be a fracture system present with no surface expression. It is also possible that the water at OLD-1 was simply meteoric water, as opposed to groundwater. But, if rainfall supplied the water directly, then the source of calcium becomes a problem to explain.

Based on the lithology and carbonate isotopes (this study) and paleobotanical data from Barboni et al. (2010) a preliminary reconstruction of the landscape in the environs of the FLK North site is presented in Fig. 10. The site was on a wooded topographic high with freshwater ponded in the adjacent depression above the fault. The interpretation of the spring is based on the presence of carbonates beds that occur most prominently during the time of archaeological levels 4 through 2 (Fig. 6). The spring began to leave a mineral record (calcite) during time of level 5. The area became mostly subaerial as the climate changed from wet to dry conditions and when flooding of the lake margin by paleo Lake Olduvai (a playa) occurred less frequently. The area was fringed by wetlands that changed to more open woodland and grassland cover to the southeast (VEK, HWK, HWKE) (Barboni et al., 2010). The reconstruction of the FLK North landscape presented here differs significantly from the fault "compartment" model for Olduvai Lowermost Bed II (Blumenschine et al., 2012). Their study centers on the FLK Fault and did not recognize the Zinj Fault as a major water-carrying conduit in the junction. Additionally, they present no data on the ecology, specifically the location of water sources or the botanical remains to support descriptions of vegetation. There is no attempt to make a direct temporal connection to the cyclicity of paleo Lake Olduvai, an alkaline lake, the major ecological feature in the basin (Hay and Kyser, 2001). Without an integration of the stratigraphic and archaeological records, it is not clear if these records are even related in time or space and thus the artifacts may well be palimpsest, as was suggested by Domínguez-Rodrigo (2009).

5.2. History of FLK North (Upper Bed I and Lowermost Bed II)

Fig. 8 is a compilation of Upper Bed I sedimentological and stratigraphic data described in this study (see Fig. 6) and archaeological data (descriptions and numbers of bones/stones) from Egeland (2008). Lowermost Bed II summary is based on reconnaissance-level stratigraphic data and a summary of archaeological information from Leakey (1971). The lowest levels in the archaeological site occur just after the deposition of the Ng'eju Tuff (1.818 + 0.006 Ma). Levels 7–9 were identified by Domínguez-Rodrigo et al. (2010), but have not been (extensively) excavated. Level 6, above, was deposited during a change to wetter climate. The interpretation of the archaeological record in level 6 is controversial ranging from an elephant butchery site (Leakey, 1971) to a multiple agent, time-averaged palimpsest (Domínguez-Rodrigo et al., 2007a) The Kidogo Tuff overlies level 6. Level 5, above the tuff, includes a hominin toe bone (OH 10), birds, reptiles, and stone tools. Level 4 has a robust carnivore signal (dung and regurgitated, partly digested bone fragments, teeth and broken mandibles of small animals) (Leakey, 1971) and formed as the climate became drier. Level 3, which also has abundant evidence of carnivores was formed as drying continued. It has a few cut-marked bones. The bone assemblages are dominated by two taxa: *P. altidens* and *A. recki* which indicates specialized carcass collectors, such as felids (Domínguez-Rodrigo et al., 2007b). The upper levels (levels 2 and 1), that have a dense concentration of bones and stones, formed under increasingly arid conditions. The groundwater-fed wetland surrounding the site, however, would have provided freshwater and perhaps edible plants during this dry phase (Copeland, 2004; Barboni et al., 2010). Tuff IF (0.4 m), the uppermost unit, was deposited on a dry lake bottom and the Olduvai basin was subsequently locked in a paleoecological crisis for a few thousand years (Stollhofen et al., 2008).

Tuff IF caps the FLK North archeological site, but has been removed locally in a few spots (Leakey, 1971). Shallow depressions (animal trails?) ~1 m deep and 3 m wide have eroded the tuff to at least level 1 in a few places (Leakey, 1971) These sculpted depressions could either be animal trails (Leakey, 1971; Ashley and Liutkus, 2002; Deocampo, 2002) or fluvial drainage channels on the lake flat. An animal track way is more likely, given the lack of physical evidence of fluvial scour or a coarse sediment lag. The depressions were ultimately in filled with reworked Tuff IF (tuffaceous clay) as the lake rose during a reversal to wetter climate (Lake Cycle 3) (Fig. 3). In these younger sediments, several features of interest require further investigation: (1) scattered artifacts and faunal remains (archaeological site 40f) occur ~1.4 m above Tuff IF; (2) a massive, freshwater carbonate deposit (Fig. 9) which formed during the dry period between Lake Cycles 3 and 4 occurs at approximately the same level as the scattered artifacts and faunal remains (site 40f); (3) an archaeological site, 40 g, a *Deinotherium* skeleton that was interpreted as a butchery site, lies 2 m above Tuff IF.

The record at FLK North archaeological site as originally documented in Leakey (1971) was comprised of Upper Bed I and Lowermost Bed II. Reconnaissance-level geological study reveal that Middle Bed II sediments overlie the section shown in Fig. 8 and these, in turn, are unconformably overlain with younger sediments, Masek Beds (Fig. 2). Beds III and IV were eroded from this site during incision of the Gorge in the Late Pleistocene.

6. Conclusions

FLK North, one of the first archaeological sites discovered at Olduvai, has remained controversial for decades. Two widely divergent views on its origin have emerged: (1) the site was used as an occupation site for meat consumption (scavenged or perhaps hunted) by hominins, or (2) the site was used by carnivores to eat their kill and hominins only occasionally passed through the area (Bunn et al., 2010). Recent research pointed to a groundwater-fed spring and wetland in the area of the site that was a likely attraction for vertebrates (prey and predators, as well as hominins) (Ashley et al., 2010a,b; Barboni et al., 2010). However, little was known about the paleoclimatic context and how climate change

may have affected site use. A newly recognized tuff, the Kidogo Tuff, within Upper Bed I is used here to correlate among outcrops having paleoenvironment records and the archaeological record at FLK North site. This is the first time that high-resolution stratigraphic analysis has been used to interpret an Olduvai site; yielding a resolution of the temporal record as little as a few thousand years and the resolution of the spatial record is a few hundred m^2.

Analysis of the newly recovered fossil bones and artifacts has shown that the bones of large animals are largely the product of felid hunting and feeding behavior, followed by hyena gnawing and breakage of some bones (Bunn et al., 2010). Reanalysis of the stone artifacts demonstrates that they are designed for battering activities more than for producing sharp-edged flakes for butchery or other cutting or scraping activities (Diez-Martín et al., 2010). These results are consistent with a recent reanalysis of the Leakey collections from the site by Domínguez-Rodrigo and Barba (2007) that concluded that hominins played a minor role in site formation, contrasted to the dominant role of carnivores.

The levels with the densest concentration of archaeological remains (levels 1 and 2) were formed during the driest portion of the Milankovitch climate cycle. However, the FLK North ridge and the associated freshwater source provided an "oasis" in this otherwise parched environment (Ashley et al., 2010a). Levels 7–9 were also formed during drier conditions, and thus may be found to have archaeological material, too, when more extensively excavated.

Tuff IF, capping the FLK North site was deposited on a dry lake bed and represents a time when the Olduvai basin was locked in a paleoecological crisis for perhaps up to a few thousand years. After the crisis, the area was again a site of hominin and carnivore use during Lowermost Bed II time. A spring producing freshwater developed between Lake Cycles 3 and 4. Based on the stratigraphic height above Tuff IF, this freshwater resource appears to occur in the same horizon as Leakey's site 40f, a report of scattered artifacts and faunal remains, 1.4 m above IF (Leakey, 1971). Excavation is needed to verify this speculation. However, several freshwater sources are known from the HWK, HWKE, and VEK area at the same approximate level in Lowermost Bed II (Liutkus and Ashley, 2003; Bamford et al., 2006; Copeland, 2007; Ashley et al., 2009; Deocampo and Tactikos, 2010). These sites also have a rich archaeological record (Ashley et al., 2009). Thus, there appears to be a consistent pattern of groundwater-fed resources associated with artifact concentrations, particularly during drier than normal conditions. Clearly, geology has a role as a predictive tool to search for sites based on these well documented associations of springs and archaeological material.

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