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Paleoenvironmental and paleoecological reconstruction of a freshwater oasis in savannah grassland at FLK North, Olduvai Gorge, Tanzania

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ABSTRACT

The records of early hominins are commonly localized both temporally and spatially even in archaeologically rich basins like Olduvai Gorge, Tanzania. The FLK North site was discovered in 1960, but the reason for the exact location of this dense concentration of fossils and stone tools on a lake-margin flat has not been explained. We present new geological and geochemical information from six excavations in upper Bed I, which revealed up to 1.4-m-thick carbonate deposits, attesting to the presence of freshwater springs in the area surrounding FLK North. The $\delta^{18}O$ signatures of the tufa are typical for meteoric water that has evolved during evaporation. Tuff IF that caps the sequence was deposited on uneven topography with the highest area a low-relief ridge between two faults at the archaeological site and lowest areas being sites of groundwater discharge. The model proposed here is that rainfall on adjacent highlands was transported to the basin where faults acted as conduits for water. Similar hydrogeological settings at modern lakes Manyara and Eyasi, currently support lush groundwater forest and woodland despite arid climate. FLK North may have been an “oasis” offering freshwater and shelter for consuming meat by both carnivores and hominins.

Introduction

Olduvai Basin has 2 million years of paleontological and archaeological records that include four hominin species. A large proportion, perhaps as much as 75% of the sites, are in the “junction”, the confluence of the main and side Olduvai River gorges (Hay, 1976) (Fig. 1). FLK North archaeological site (hereafter FLK N) possesses one of the densest concentrations of fossils and stone tools found in the Gorge. The interpretations of the records were for some decades highly controversial, regarding the relative contribution of carnivores and hominins to site formation (Leakey, 1971; Bunn and Kroll, 1986; Fernandez-Jalvo et al., 1998).

Excavations of FLK N by Mary Leakey in the early 1960s exposed six archaeological levels in uppermost Bed I, 6 (oldest) to 1 (youngest) in 2.0 m of sediment (Leakey, 1971) and spanning about 20,000 yr of history (Fig. 2). The time duration is estimated from the sedimentation rate of non tuff lithologies (mainly claystones) by using either 0.12 mm/yr (Hay, 1976) or 0.1 mm/yr (Ashley, 2007) between dated tuffs (Tuff IB and Tuff IF). The archaeological levels occur immediately under Tuff IF at the top of Bed I dated at ~1.785 Ma (Hay and Kyser, 2001). The age of Tuff IF is nearly coincident with the top of the paleomagnetic interval CN2 (Fig. 2). Recent (2007–2009) excavations at FLK N by TOPPP (The Olduvai Palaeoanthropology and Palaeoecology Project) have added levels 7–9 (Domínguez-Rodrigo et al., 2010) (Fig. 2).

Leakey thought the archaeological levels to be dominantly anthropogenic (Leakey, 1971). She interpreted level 6 to be a butchering site of an elephant (complete with stone tools) and levels 5 to 1 to be “living floors”, i.e. deposits representing *in situ* evidence of occupation, such as discarded artifacts and bones. A re-evaluation of her data from levels 1–5 suggests that the bone concentration is dominantly a product of carnivore activity, namely felids and hyenas (Domínguez-Rodrigo et al., 2007). This was confirmed by recent (2007–2009) excavations in levels 1–2 by TOPPP, which yielded > 1000 new large mammal fossils that show minimal evidence of butchery by hominins and abundant evidence of carnivore gnawing and fracture and rodent gnawing (Bunn et al., 2010).

Although there is no consensus on how the bones and stones accumulated, there is agreement by excavators that the site is

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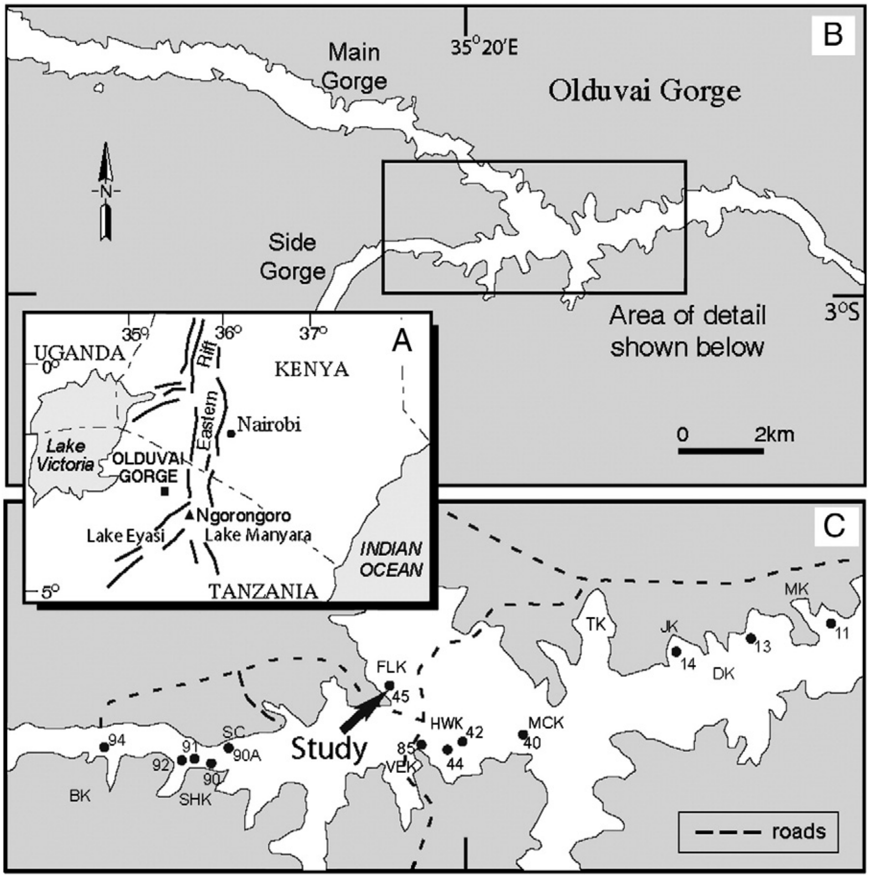

Figure 1. A. The inset map shows the location of Olduvai Gorge, Tanzania within the eastern branch of the East African Rift System and location of possible modern analogs of FLK N paleoecology, Lake Manyara and Lake Eyasi. B. Map of Olduvai Gorge depicts the "junction", the confluence of Main and South branches. C. More detailed map of the junction area with key archaeological and geological sites. Locality designations (letters) are according to Leakey (1971); the geology locations (numbers) from Hay (1976). The study site (arrow) is included in the FLK (45) area.

nonstratified. Leakey (1971) found no recognizable pattern of distribution except for clumps of crushed bones in regurgitated material and in coprolites. Domínguez-Rodrigo and Barba (2007) describe the archaeology in level 1-2 to be vertically distributed and most likely time-averaged. A recent taphonomic re-evaluation of Leakey's collection suggests that it was a palimpsest in which most of the bones were accumulated and modified by carnivores and the site represents extensive periods of time between depositional events (Domínguez-Rodrigo and Barba, 2007). The lithic tools, therefore, seem to have an independent depositional history from most of the fauna. However, the reason for the geographic location of the site remains a puzzle and determining this is central to understanding site formation by hominins or carnivores. The underlying factor(s) determining the exact location of FLK N, its longevity (persistence or re-occupation) has remained obscure. There are no published interpretations of the site that satisfactorily explain why the site formed where it did. For example, there is no evidence for a riverine habitat and although the area is situated on a lake margin the Paleolake Olduvai water was not likely potable. The lake was a saline and alkaline playa, based on mineralogical analyses of the lake sediments (Hay and Kyser, 2001; Blumenschine et al., 2003; Hover and Ashley, 2003; Deocampo et al., 2009). Analyses of macrofauna (Plummer and Bishop, 1994; Andrews and Humphrey, 1999), microfauna (Fernandez-Jalvo et al., 1998), pollen (Bonnefille, 1984), paleosols (Sikes and Ashley, 2007), and phytoliths (Bamford et al., 2008) suggest a time of drying climate and a preponderance of open space, i.e. grasslands. It was also a time of falling lake level (Ashley, 2007). But, the apparent longevity of the site suggests a persistent natural resource that encouraged visits to the site over a period of several thousand years. The objectives of this paper are to reconstruct the paleoenvironment and paleoecology during upper Bed I time to provide insights into the reason(s) for the location of the site and its persistence through time, and to better understand palimpsest site formation.

Background

Geologic setting

The Olduvai Basin is situated on the western margin of the East African Rift south of the equator (3°S) between Precambrian basement to the west and the early Pleistocene Ngorongoro Volcanic Highland to the east (Fig. 1A). The Gorge cuts across a 50 km wide rift-platform basin and exposes a 2 myr sedimentary record in an incised river valley system draining eastward from the Serengeti Plains. The Pleistocene basin fill is thin (100 m) and composed largely of reworked volcaniclastic sediment and air fall tuffs deposited in a shallow semi-arid fluvial–lacustrine basin (Figs. 2 and 3) (Hay, 1976; Ashley and Hay, 2002). The Olduvai sedimentary basin was affected by extensional tectonics associated with the rift. Most notable are the rift parallel normal faults that cross the basin (Figs. 3 and 4A) (Hay, 1976).

The sedimentary record contains a rich faunal and cultural record of early hominins and thus is important to human evolutionary studies (Leakey, 1971; Blumenschine and Masao, 1991; Feibel, 1997; Ashley, 2000; Blumenschine et al., 2003; Dominguez-Rodrigo et al., 2007). The stratigraphic record above the basal volcanics is divided into six units, Bed I to Ndutu Beds (Fig. 2) and a basin-wide stratigraphic framework

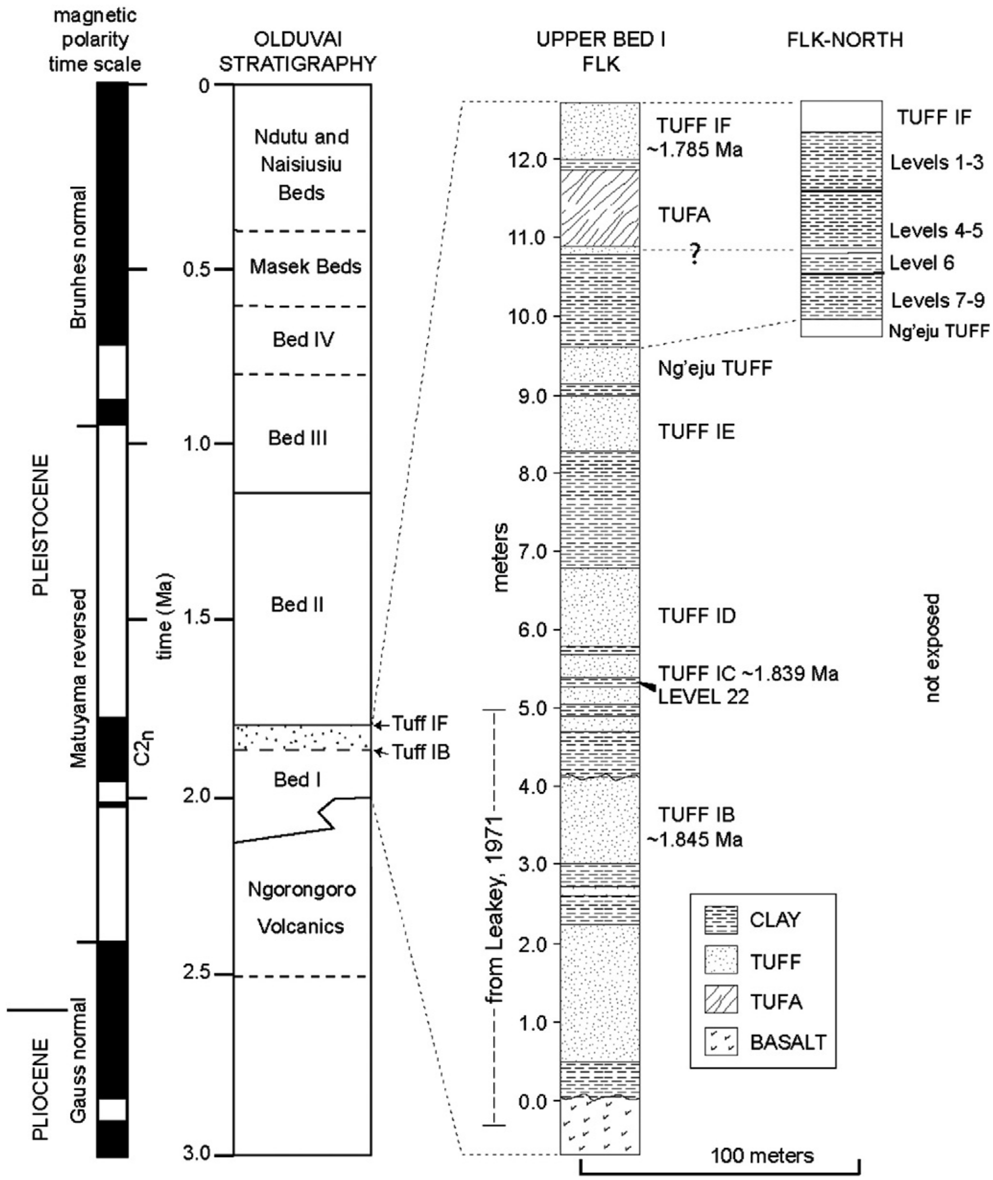

Figure 2. The Pleistocene magnetic polarity time scale is shown adjacent to the Olduvai basin stratigraphy (modified from Hay, 1976). The stratigraphy of upper Bed I from FLK and micro-stratigraphy in study site (FLK N) are shown in expanded sections.

has been established using detailed field mapping, mineral chemistry, $^{40}Ar/^{39}Ar$ dating and paleomagnetic studies (Gromme and Hay, 1971; Hay, 1976; McHenry, 2004; McHenry, 2005).

The dominant lithology (~70%) is waxy clay with varying amounts of carbonate (tufa) (~20%) and thin beds of tuff (~10%). Clay was deposited by the lake during periodic flooding of the lake margin, the carbonate was precipitated from groundwater seeps or springs, and the tuff is derived from periodic eruptions of volcanoes in the Ngorongoro Volcanic Highland (Hay, 1976; Ashley and Hay, 2002; McHenry, 2004). The clay ranges from olive brown to yellowish brown, and contains about 10% silt, minor sand and occasional pebbles. The dominant clay minerals are Mg-rich smectite and interstratified illite (Hay, 1976; Deocampo and Ashley, 1999; Hover and Ashley, 2003). Pedogenic features, such as peds, slickenslides, root markings and/or rhizoliths are present, as are calcite nodules and concretions (Sikes and Ashley, 2007).

Paleoclimatic setting

Paleoclimatic variability near the equator during the Pleistocene was regulated by Milankovitch astronomic cycles (precession modulated by eccentricity), superimposed on a long-term cooling and drying trend (deMenocal, 1995; Ruddiman, 2000; Ravelo et al., 2004; Deino et al., 2006; Sepulchre et al., 2006; Maslin and Christensen, 2007; Trauth et al., 2007). The ~19–23 ka long Milankovitch cycles produce wet–dry periods resulting from changes of solar insolation that in turn modulate the Asian monsoon (Ruddiman, 2000). The Asian monsoon brings moisture to East Africa from the Arabian Sea, whereas central and west Africa receives moisture from the Atlantic Ocean (Nicholson, 1996; Levin et al., 2009). When solar insolation is higher, the strength of the summer monsoon increases the annual rainfall (Rossignol-Strick, 1983; Ruddiman, 2000), and the climate becomes wetter, leading to more water on the surface in the form of rivers, lakes, and wetlands (Street and Grove, 1979; Kutzbach and Street-Perrott, 1985a; Kutzbach and Street-Perrott, 1985b). As lake levels rise, the vegetation is likely to respond as well (Kutzbach and Street-Perrott, 1985b; Hughen et al., 2004; Wang et al., 2008).

On the short term, precipitation near the equator is modulated by the annual migration (back and forth) of the Intertropical Convergent Zone (ITCZ), the boundary where winds originating in the northern

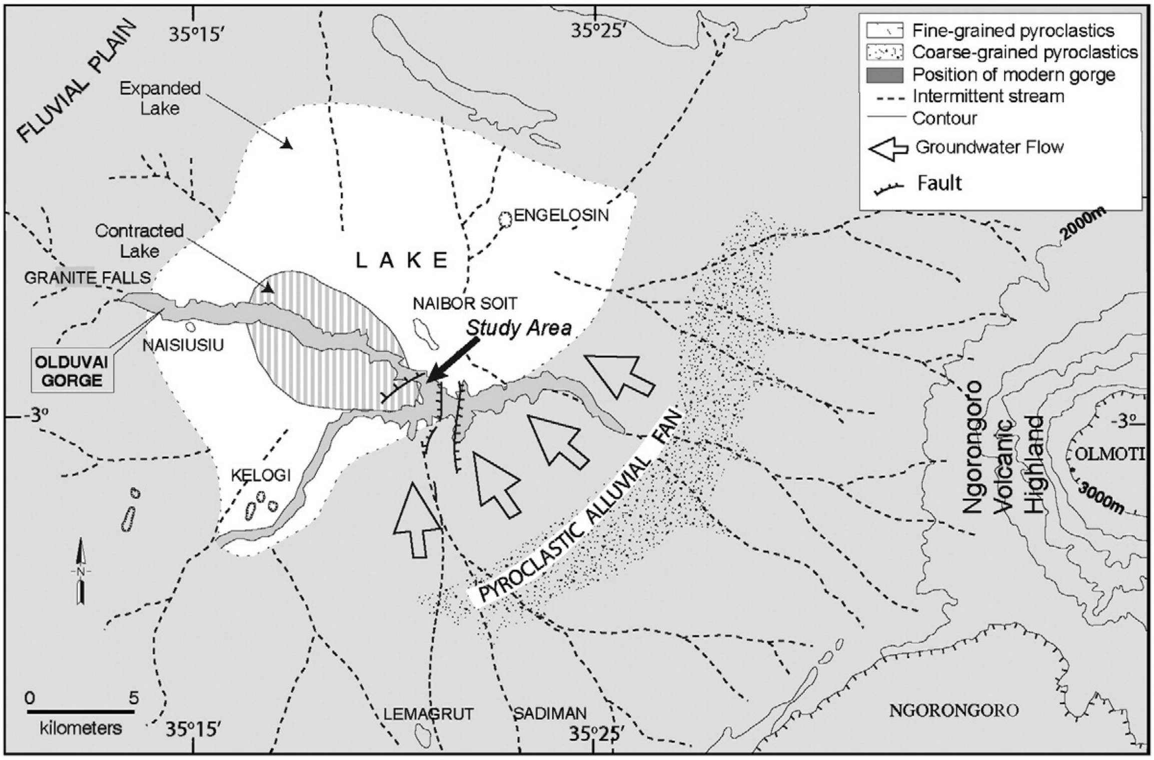

Figure 3. A paleogeographic reconstruction of the Olduvai basin with the ~3000 m high Ngorongoro Volcanic Highland to the east and Paleolake Olduvai in a broad basin (after Hay, 1976). The area covered by the lake varied with fluctuating lake level; the maximum lacustrine area is estimated at 200 +/− 50 km^2. Study site (arrow) is located on paleolake margin.

and southern hemispheres come together (Nicholson, 1996). The migration of the ITCZ produces two rainy seasons annually in the Olduvai region, long rains (April–May) and short rains (Nov–Dec). The modern annual precipitation is 550 mm/yr and the annual evapotranspiration may exceed 3000 mm/yr (Hay, 1976). Rainfall also varies on sub-Milankovitch scales over decades and millennia (Nicholson, 2000), but these short-term climate variations are not likely recorded as individual events in the sediment record. However, a study of stable isotopes of lake-margin carbonate rhizoliths in wetland deposits in lowermost Bed II provided strong evidence of short-term (decadal to centennial scale) climate fluctuations at Olduvai (Liutkus et al., 2005).

Hydrologic setting

Olduvai Gorge is situated on the leeward side of a major topographic high, the Ngorongoro Volcanic Highland (~3000 m) (Figs. 1 and 3). The Highland receives nearly twice the rainfall (1037 mm/yr) as the adjacent Olduvai lowland (550 mm/yr), due to elevation difference and a rain-shadow effect (Deocampo, 2004). This precipitation difference was likely true in the past. Moisture-laden prevailing easterly winds from the Arabian Sea are trapped by the Highland, which is a potential recharge area for local aquifers. The hydrologic model for paleo Olduvai basin proposed here is speculative, but is soundly based on the general understanding of groundwater flow in closed basins (Duffy and Al-Hassan, 1988; Rosen, 1994; Meijerink and Van Wijngaarden, 1997). The ideas have been used in a number of recent Olduvai studies (Ashley and Driese, 2000; Ashley and Hay, 2002; Liutkus and Ashley, 2003; Ashley et al., 2008). The model proposes that rainfall on adjacent highlands was transported into the basin. Groundwater moving under hydraulic head moved downhill in a westerly direction and disgorged onto the surface when encountering impervious beds, faults or the basin floor, such as on the fault bounded margins of present-day lakes Manyara and Eyasi (Fig. 1A).

Methods — field and laboratory

We opened six trenches (FLK-W, FLK-N, FLK-02, FLK-NW, FLK-N-3, FLK-01) ranging from 2 to 2.5 m thick between Ng'eju Tuff and Tuff IF at the top of Bed I (Fig. 2). The stratigraphic section (FLK-N) was open at FLK N, the archaeological site, and five additional sections from a 15,000-m^2 area surrounding the site were also studied to determine the paleoenvironment at the time of site formation (Fig. 5). Stratigraphic sections were described and logged using scaled drawings and photographed. Representative sediment samples were collected for analyses and site locations documented with GPS (Table 1). The stratigraphic sections are on two NW–SE transects that begin at the FLK Fault and cross the Zinj Fault (Fig. 4B). Transect A–B starts near the FLK Fault, passes through (archaeological site), crosses the Zinj Fault and ends at stratigraphic section FLK-02. Transect C–D lies 75 m to the northwest and is parallel to Transect A–B. Transect C–D starts near the FLK Fault, passes through section FLK-N-3 and ends at FLK-01.

Carbonate beds and mounds were observed in the five sections surrounding the site. To identify the origin of these carbonates, 21 samples were collected and analyzed for C and O at the Stable Isotope Laboratory at Rutgers University on a Micromass Optima Mass Spectrometer. Samples were loaded into a MultiPrep™ peripheral and reacted in phosphoric acid at 90°C for 13 min. The $\delta^{13}C$ and $\delta^{18}O$ values are reported relative to V-PDB through the analysis of an internal laboratory standard which is routinely checked vs. NBS-19 (Coplen et al., 1983). The deviations of the internal lab standard from NBS-19 are 0.10 and 0.04‰ for $\delta^{13}C$ and $\delta^{18}O$, respectively. The 1-sigma deviations of the lab standards analyzed during the sample analyses are 0.05 and 0.08‰ for $\delta^{13}C$ and $\delta^{18}O$, respectively. The raw

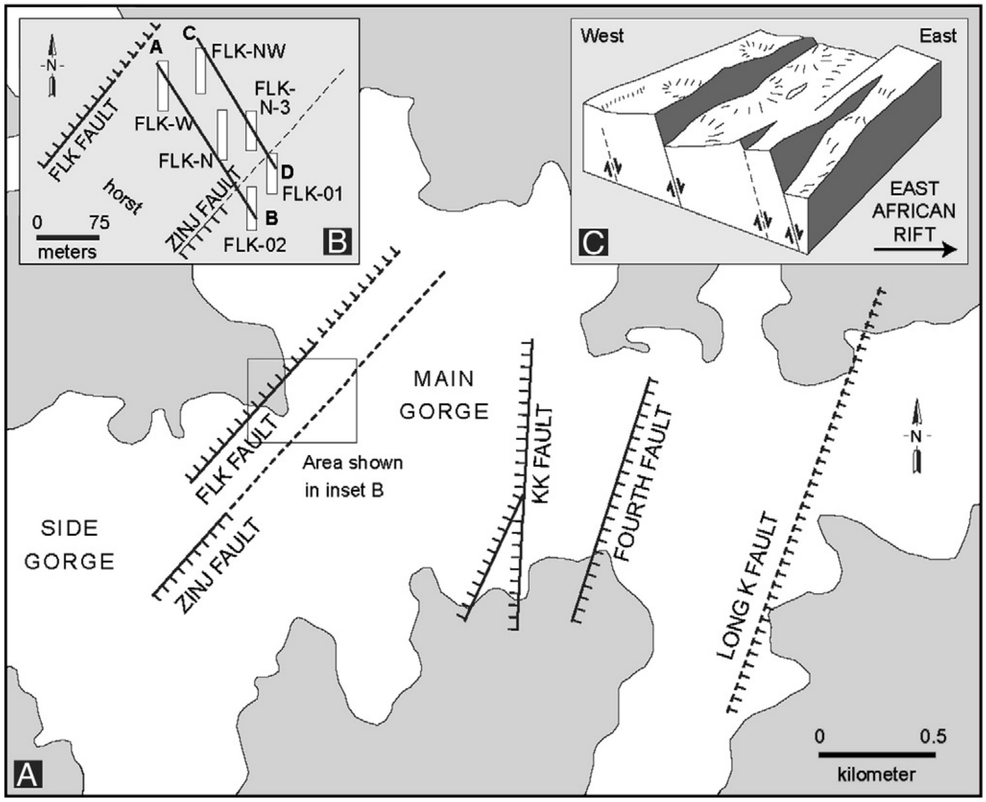

Figure 4. A. Map of the faults in the junction area. The normal fault, herein named Zinj Fault was mapped by Hay (1976), but the projection of it to the northeast is interpreted in this study. B. Inset depicts an enlargement of the FLK and Zinj faults and the location of the stratigraphic sections shown in Figure 5. C. Inset is a diagrammatic sketch of typical rift-related extensional faulting showing normal faults and fractures in various stages of formation (after Gawthorpe and Leeder, 2000).

data are summarized (Table 2) and sampling locations are shown in Figure 5.

Results

The micro-stratigraphy of the six sections is highly varied given that the deposits are closely spaced within 200 m of each other. They are composed of similar lithologies, waxy clay, tuff and carbonate (tufa) beds, but show no systematic stratigraphic pattern (Fig. 5). The section FLK-N in the archaeological site has no tufa and is composed predominately of waxy clay with a thin (10 cm) tuff layer that is similar in texture and in nearly the same stratigraphic position as a thin tuff bed in FLK (Fig. 2). These thin tuff beds may correlate. The other five sections have varying amounts of carbonate, clay and tuff, but show no systematic pattern in terms of bed thickness or composition of juxtaposed beds. Essentially all the waxy clay beds show evidence of pedogenesis (peds, prisms, root traces, concretions, cutans, and slickensides) and are classified as vertisols (Retallack, 2001).

The carbonate occurs in beds 0.2–0.5 m thick and a mound up to 1.4 m thick. Individual tufa beds can be traced laterally for tens of meters. The thinner beds varied in thickness and in places pinch out. The tufa ranges from stark white to light yellow and tan and the texture varies from spongy and soft to nodular. Clay is admixed in the tufa as isolated blebs, thin beds and streaks. There does not seem to be any pattern in deposition with time (i.e., between Ng'eju Tuff and Tuff IF). In summary, sediments are dominantly lacustrine clays deposited during flooding of the lake margin with interbeds of tufa produced by spatially localized and episodic disgorging of groundwater (springs or seeps) and an occasional pyroclastic airfall.

The stable isotope analyses of the carbonate samples from the five stratigraphic sections provide some insights into the water source. The $\delta^{18}O$ ranges from ~−6 to 0‰ V-PDB and $\delta^{13}C$ ranges from ~−5 to +3‰ V-PDB (Table 2, Fig. 6). The data are clustered in two almost exclusive fields, those samples collected in the vicinity of the Zinj Fault (FLK-01, FLK-02 and FLK-N-3) and those samples collected in the vicinity of the FLK Fault (FLK-W and FLK-NW), which have a more evolved signature. The precipitation in this region of East Africa is reported to have $\delta^{18}O$ values of −4.0‰ V-SMOW (Bowen, 2010).

Discussion

The archaeological site was formed prior to the deposition of Tuff IF (~1.785 Ma) (Fig. 2). The regional climate was in a drying period at the end of Bed I (Ashley, 2007; Sikes and Ashley, 2007) which would have decreased the overall moisture balance (i.e. less precipitation, continued high evaporation) and on the long-term lowered the lake level (Fig. 3). This overall drying trend has been noted by previous researchers using a range of paleoenvironmental indicators (Bonnefille, 1984; Kappelman, 1986; Plummer and Bishop, 1994; Hay and Kyser, 2001; Sikes and Ashley, 2007; Bamford et al., 2008). However, Paleolake Olduvai was in a broad shallow basin with an extensive fringing lake-margin plain and thus subject to short-term lake flooding (evidenced by deposition of lake clay) in exceptionally wet years even during overall dry periods.

The dominant sediment type in the vicinity of FLK-N as revealed in the six sections is massive, but pedogenically modified lake clay (~70%) (Figs. 2, 4 and 5). The lack of stratification is likely due to a combination of sediment mixing, such as soil forming processes (wetting and drying), penetration by plant roots, and likely bioturbation by animals (insects to large vertebrates animal) (Ashley and Liutkus, 2002). The extensive evidence of pedogenesis suggests long periods of subaerial exposure in between lake flooding events allowing for soil forming processes to modify the smectitic clay. Occasionally pyroclastic eruptions in the Ngorongoro Volcanic Highland produce tephra that was carried to the Olduvai basin on the prevailing westerly winds (Hay, 1976; McHenry, 2004; Mollel, 2007).

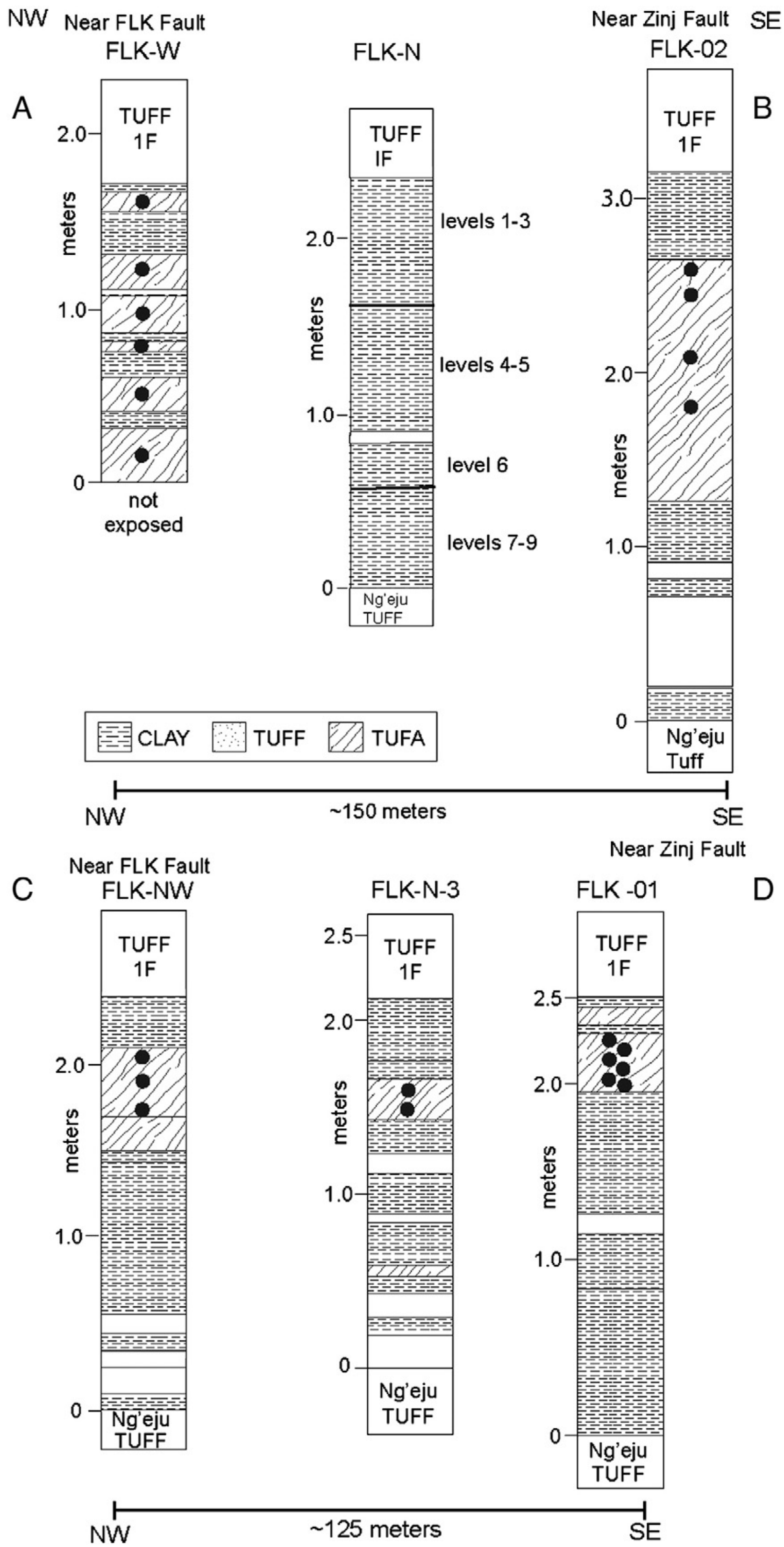

Figure 5. Top. Micro-stratigraphy of the area near the FLK N archaeological site as revealed in sections FLK-W, FLK-N and FLK 02 along NW-SE transect A–B. Location of sections with respect to faults is on Figure 4B. FLK-02 has a 1.4-m-thick tufa deposit and is likely near or right on the Zinj Fault; FLK N has no carbonate and is between the faults; and FLK W situated near to the FLK Fault has intercalated tufa and waxy clay deposits. Location of the twenty-one tufa samples analyzed for stable isotopes (Table 1) are shown as black dots. Bottom. Micro-stratigraphy of the area near the FLK N archaeological site as revealed in sections FLK-NW, FLK-N-3 and FLK-01 along NW-SE transect C–D. Location of sections with respect to faults is on Figure 4B. The sections have tufa deposits ranging for 0.3 m–0.6 m thick. Based on location, FLK-01 and FLK-N-3 likely received water from the Zinj Fault, whereas FLK-NW more likely received water from the FLK Fault.

Table 1
Location of stratigraphic sections.

Year[a]	Location[b]	Trench	Lat./Long.
2007	FLK	FLK-01	2°59.387′S 35°20.927′E
2007	FLK	FLK-02	2°59.393′S 35°20.898′E
2008	FLK N	FLK-N	2°59.347′S 35°20.888′E
2008	FLK N	FLK-N-3	2°59.340′S 35°20.902′E
2009	FLK NN	FLK-NW	2°59.312′S 35°20.858′E
2009	FLK NN	FLK-W	2°59.305′S 35°20.835′E

[a] Year of trench logging.
[b] Following Hay (1976).

Table 2
Stable isotope data by locality.

Locality	Height[a] (m)	Sample #	Δ^{18}O	Δ^{13}C
FLK-01	1.95	GA-Old-17-07	−5.3	−4.5
FLK-01	2.00	GA-Old-47-07	−5.2	−4.2
FLK-01	2.05	GA-Old-16-07	−4.9	−3.3
FLK-01	2.10	GA-Old-46-07	−4.9	−3.2
FLK-01	2.20	GA-Old-15-07	−4.6	−2.8
FLK-01	2.30	GA-Old-45-07	−4.4	−2.0
FLK-02	1.80	GA-Old-53-07	−5.3	−3.7
FLK-02	2.15	GA-Old-52-07	−4.1	−2.1
FLK-02	2.50	GA-Old-51-07	−5.4	−4.4
FLK-02	2.75	GA-Old-50-07	−5.0	−3.7
FLK-N-3	1.50	GA-Old-72-08	−4.2	−2.5
FLK-N-3	1.65	GA-Old-73-08	−3.9	−2.5
FLK-W	1.65	GA-15-09	−5.0	−2.7
FLK-W	1.25	GA-17-09	−3.1	−0.3
FLK-W	1.00	GA-18-09	−2.5	1.0
FLK-W	0.75	GA-19-09	−3.2	0.3
FLK-W	0.45	GA-20-09	0.04	2.8
FLK-W	0.15	GA-21-09	0.1	2.6
FLK-NW	2.10	GA-53-09	−4.9	−1.1
FLK-NW	1.95	GA-54-09	−5.3	−1.3
FLK-NW	1.80	GA-55-09	−2.6	0.9

[a] See Figure 5.

The stable isotope signatures of tufa (calcite) record both physical and biological processes in the depositional environment. The carbon isotopic composition of the calcite is a combination of the δ^{13}C of dissolved inorganic carbonate, input of land–plant debris, as well as organic matter degradation (pre-burial) and diagenesis (post-burial) (Deocampo, 2010). In this study, we focus on the oxygen isotopes as they more faithfully record the source of the water, whereas the carbon signature reflects the composition of the host lithologies of the aquifer (sediment and bedrock). The oxygen isotopic composition of the carbonate is controlled by the composition of the groundwater that in turn is initially inherited from the composition of the rainfall and later affected by temperature- and evaporation-related fractionation (Deocampo, 2010). The average temperature (~25°C) does not vary much on a seasonal basis and precipitation in this equatorial region is reported to have δ^{18}O values of −4‰ V-SMOW) (Bowen, 2010) (Fig. 6). Calcite precipitated under these temperatures (with little to no evaporation) will have δ^{18}O (V-PDB) values of ~−6‰ (O'Neil et al., 1969; Liutkus et al., 2005).

The tufas collected from sites near the FLK Zinj Fault (FLK-01, FLK-02 and FLK-N-3) show δ^{18}O signatures between −4 and −6‰, which indicates direct precipitation of calcite from flowing water with very little evaporation. This information supports the facts that the tufa associated with the Zinj Fault occurs in a mound form and is thick-bedded (Figs. 5 and 7). The samples near the FLK fault (FLK-W and FLK-NW) have a different history. The effect of evaporation on the δ^{18}O signature of calcite precipitated from spring water as it flowed or seeped onto the surface appears to have been significant. The tufas associated with the FLK Fault have δ^{18}O values that are considerably evolved (more positive) suggesting evaporation of the groundwater

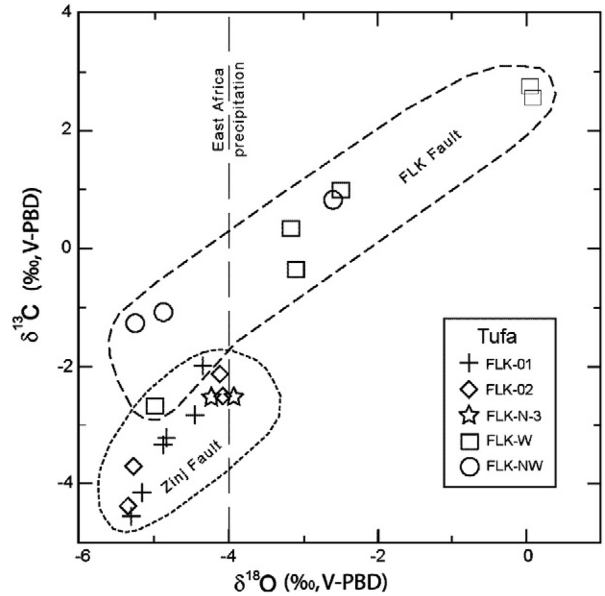

Figure 6. Plot of stable isotope ratios of δ^{13}C versus δ^{18}O of carbonate (tufa) sediments from sites in the vicinity of the FLK N archaeological site. The East Africa precipitation that has a δ^{18}O of −4.0 V-SMOW is indicated (Bowen, 2010). Carbonates emanating from the Zinj Fault are very close to the meteoric signature indicating very fresh water, whereas the carbonates found near the FLK Fault have a much more evolved signature, suggesting groundwater seeps with extensive evaporation prior to and during formation.

causing fractionation of the isotopes and an increase of δ^{18}O over δ^{16}O. This geochemical information in conjunction with the sedimentary record of thin tufas interbedded with clay (e.g., FLK-W, Fig. 7) indicates intermittent groundwater discharge, perhaps as seeps.

Carbonate is unevenly distributed throughout the sediment record above the Ng'eju Tuff both in time and space, but there are some important things to note. First, the stable isotope signature of the tufa is freshwater and thus likely derived from ground water flowing to the site. Second, no tufa occurs at FLK-N, but is present at all other sites, suggesting that FLK N was on higher ground as surface water seeks low areas. A slight topographic high was revealed by the draping of Tuff IF over it (Fig. 7). Tuff IF thickness data from Hay (1976) documents that Tuff IF is thinner (0.4 m) at FLK-N and is thicker (0.6–0.7 m) in the adjacent areas of the Zinj Fault (FLK-01 and FLK-02) and FLK Fault (FLK-W). Field observations of Tuff IF revealed the same tephra facies at the base of the tuff overlying the sediments and there appeared to be no post-depositional erosion of the top of the tuff prior to the deposition of lowermost Bed II sediments. The pyroclastic drape indicates that a low-relief mound, probably a ridge was present at the time of deposition of Tuff IF. The ridge may have been related to a horst, an uplifted block between the two faults (Fig. 4C). Both faults were originally mapped by Hay (1976, his Fig. 3), but this study projects the more southerly fault (herein named the Zinj Fault) as a fault line to the study site, because its presence is strongly suggested by the exceptionally thick tufa deposits (Figs. 5 and 7). Current outcrops do not allow determination of the structural details of the faults, specifically whether they were through-going faults, scissor faults, or simply fractures as shown in the diagrammatic figure from Gawthorpe and Leeder (2000) (Fig. 4C).

The analysis of phytoliths (micro-botanical remains composed of silica) from 10 over 14 samples collected immediately (<5 cm) under tuff IF in or near the geological sections we describe here, revealed abundant (>50%) phytoliths attributed to woody plants including trees, shrubs, palms, with copious sedges and few grass silica short cells in the vicinity of FLK N (Barboni et al., 2010) (Fig. 8A). Examples are globular echinate types (Fig. 8C-a) from Palmae (but unidentified with respect to genus) and globular granulate (Fig. 8C-b) from

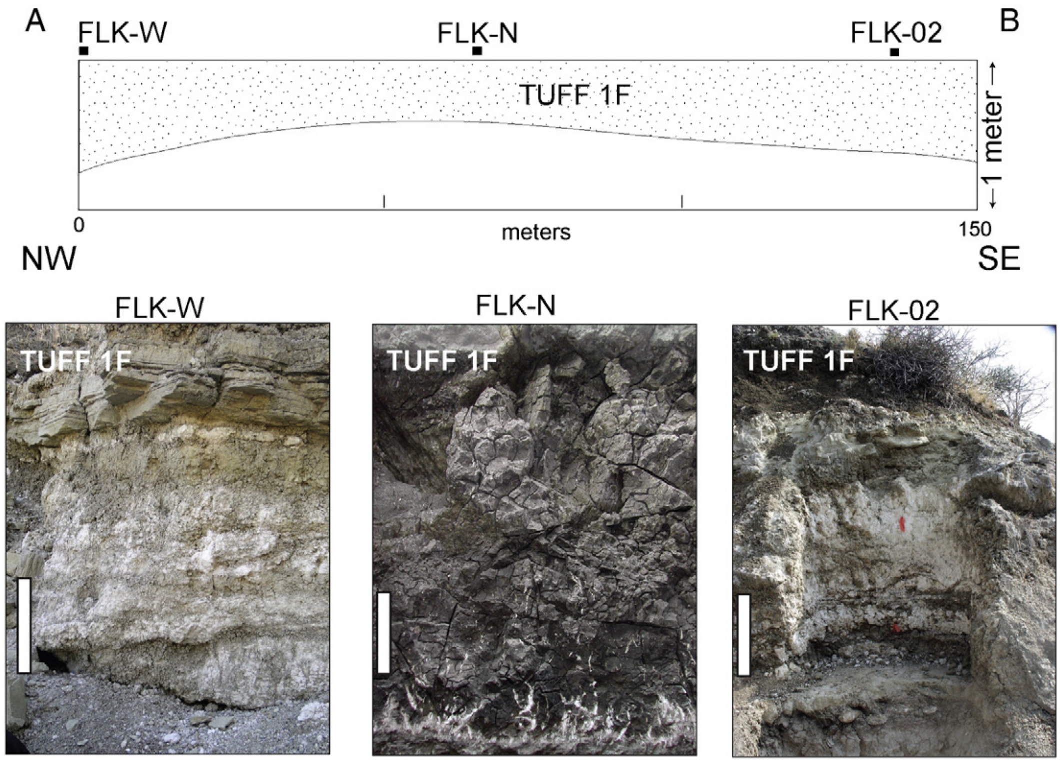

Figure 7. Sketch of Tuff IF thickness over a 150-m-long NW–SE transect from FLK-W near FLK Fault (0.7 m) to FLK-N at the study site (0.4 m) to FLK-02 near the Zinj Fault (0.6 m) based on data from Hay (1976). Photos from each site reveal different sediments directly under marker bed Tuff IF; FLK-02 has thick clay underlain by thick tufa, FLK-N is dominantly clay, and FLK-W is intercalated thin clay and tufa beds. Scale on each photo is 0.5 m. The thinning of tuff at FLK-N is interpreted to reflect a topographic high on the landscape at the time Tuff IF was deposited.

unidentified woody dicotyledons (trees and shrubs). Other morphologies, such as the irregular silica body with longitudinal facets and smooth surface (sclereid) are also thought to come from woody dicotyledons (unidentified) (Fig. 8C-c) (Runge, 1999; Strömberg, 2003). Sites adjacent to the archaeological site, FLK-W, FLK-NW and FLK-02 contain phytoliths attributed to both woody dicots and sedges indicating wet environments. The area in the vicinity of FLK N was densely wooded (woody cover >50%) with trees or shrubs or both, and palms, and is best described as a groundwater forest. Distal sites in the junction to the south and east of the 15,000 m^2 study area (HWK and VEK) (Figs. 1 and 8A) have more grass phytoliths (10 to 45%) with some localized palms (Barboni et al., 2010). This terrain can best be described as wooded grassland. A previous study on the clays beneath Tuff IF, but focusing on silicified macroplant remains is consistent with the interpretation of a grassland (Bamford et al., 2008).

The phytoliths recovered from the six sites in the study area (15,000 m^2) indicate abundant woody plants and sedges, but rare grasses, which suggest high soil water availability in the area surrounding FLK N archaeological site. At FLK N, the presence of palm phytoliths suggest well-drained soils (Greenway and Vesey-Fitzgerald, 1969), which is consistent with our interpretation that the archaeological site was higher (+ 1 m relief) based on the draping of Tuff IF over a "high" (Fig. 7). Re-evaluated published pollen data (Bonnefille, 1984) shows that 70% of the fossil pollen signal may be attributed to woody plant formations including thicket-woodland, *Acacia* groundwater woodland, gallery and groundwater forests, while ~30% is attributed to swamp herbage and grasslands (Barboni et al., 2010). This was done by grouping pollen taxa according to their affinity with extant vegetation communities of Lake Manyara. Despite the current semi-arid climate, forest and bushlands occur today along the margins of Lake Manyara supported by groundwater seeps (Greenway and Vesey-Fitzgerald, 1969; Loth and Prins, 1986). Forest with >80% woody cover occur at the spring heads, while bushlands with 20–60% woody cover (predominantly shrubs of Capparidaceae *Salvadora persica*, trees of *Croton macrostachyus*, Acacias, and C4-Chloridoideae grasses) occur in association with the palm *Phoenix reclinata* in the locally better-drained areas. Thus, the analogy with current hydrogeological settings of Lake Manyara is strengthened by previous pollen studies, which attest to the presence of thicket-woodland, *Acacia* woodland and groundwater forest taxa despite the abundance (and known over-representation) of grass pollen (Bonnefille, 1984).

Based on the evidence of sedimentology and stratigraphy the paleoenvironmental reconstruction of FLK N is interpreted to be a low-relief ridge positioned on a NE–SW oriented horst between rift-related faults (Figs. 4 and 8). Based on the hydrogeological context of and the phytolith and previous pollen data, paleovegetation at FLK N is interpreted to be similar to present-day groundwater forest, thicket- and *Acacia*-woodlands associated with springs at Lake Manyara (Fig. 1A). However, based on earlier reconstructions by Hay (1976), the site was thought to be situated on a wide, flat lake-margin plain that was periodically inundated with lake water (Fig. 3). Overall it was likely a wooded grassland with a dense bushland and forest patches in spring-fed areas such as in the close vicinity of the FLK N archaeological site (Fig. 8) (Barboni et al., 2010). Studies in the vicinity of VEK and HWK in Bed II immediately overlying Tuff IF have abundant evidence for freshwater (Deocampo et al., 2002), well-documented springs and a large wetland (Liutkus and Ashley, 2003) and wood from large trees at HWK (Bamford, 2005).

At the time of the formation of the archaeological levels (Fig. 2), the climate was drying out and thus the lake-margin flooding would have been less frequent (Ashley, 2007; Sikes and Ashley, 2007). Groundwater flowed periodically from faults that acted as conduits. Groundwater is shielded from the high evaporation (<3000 mm/yr) that occurs near to the equator. The freshwater tufa that was forming just prior to the deposition of Tuff IF, and at about the same time as

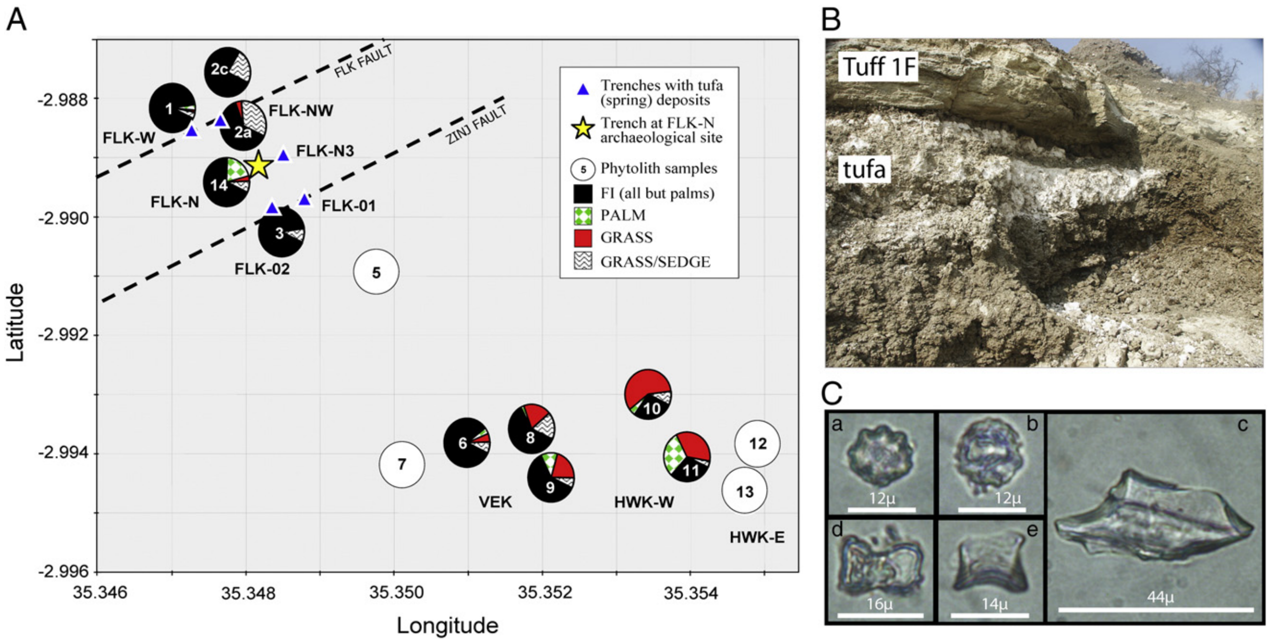

Figure 8. A. Uppermost Bed I paleoenvironmental reconstruction within the "junction area" of Olduvai Gorge showing the position of interpreted groundwater-fed spring centers (triangles) relative to the Zinj Fault and FLK Fault, and the proportions of forest-indicator phytoliths versus grassland-indicator phytoliths as pie diagrams (Barboni et al., 2010). FLK N archaeological site (star) occurs between the faults in an area surrounded by dense woody vegetation that may be forest, woodland, or bushland with scattered palm trees. About 500 m to the southeast of FLK N, more open vegetation with more grasses occur at VEK and HWK-W, also with scattered palms. B. Photo of tufa at FLK-01 in upper Bed I capped by Tuff IF. This freshwater occurs at the same time as Levels 1–3 at FLK N. C. Example of forest indicator (FI) phytoliths and grass-indicator phytoliths observed in 10 over 14 samples collected in uppermost Bed I (Barboni et al., 2010). C-a: phytolith globular echinate (palms), b: globular granulate, c: sclereid, (b–c, from undifferentiated woody dicots), d–e: grass silica short cells, d: bilotate type, e: rondel type.

archaeological levels 1-2 and 3 at FLK N, occurs about 100 m away in the FLK-01 section near the Zinj Fault (Figs. 4, 5, 7, and 8). The presence of flowing spring water, coming from the FLK Fault zone, is recorded by interbedded tufas at FLK-NW and FLK-W (Figs. 4, 5, 7, and 8). The groundwater discharged episodically (based on the intercalated tufa and clay beds) (Fig. 5) and discharged slowly based on the heavy $\delta^{18}O$ signature suggesting considerable evaporation during carbonate precipitation (Fig. 6).

Thus, the localization of the archaeological site appears to have been caused by geologic and hydrologic factors (i.e., proximity to fault-controlled springs) that also help explain the marked longevity of the site and its palimpsest characteristics. The wooded vegetation, most likely thicket-woodland with predominantly shrubs and scattered trees interpreted for could explain the persistence and re-occupation of the site by carnivores and occasional hominins. Studies of the faunal remains are consistent with our findings of a closed and wet woodland (Andrews, 1983; Andrews and Humphrey, 1999). Carnivores could find refuge among trees to consume carcasses obtained from nearby open-habitat spots. Open-vegetation habitats may support strong competition among carnivores with frequent overlap of different taxa in the use of space and its resources (Blumenschine, 1986; Domínguez-Rodrigo, 2001).

Trophic dynamics system describes the position that an organism occupies in a food chain, more specifically what an organism eats and what eats an organism. It is useful when interpreting the taphonomic signature of dense concentrations of bones at FLK N (Domínguez-Rodrigo, 2001). For example, the high trophic dynamics among the predatory guild results in taphonomic signatures defined by low survival of (long) bones per prey-carcass individual, low survival of cancellous bone, high fragmentation of long bones and, very few bones from small carcasses preserved (Blumenschine, 1989; Domínguez-Rodrigo, 1996). The taphonomic signature of faunal remains unearthed at FLK N (Bunn et al., 2010; Domínguez-Rodrigo et al., 2010) is characterized by an abundance of long bones per individual represented, cancellous bones (in the form of axial elements, flat bone and epiphyseal portions) are well represented (>30% of the assemblage), a large portion of the long bones are either complete or preserve the complete shaft circumference (>50%) and small carcass bones are the second largest portion of the assemblage (Bunn, 1986; Domínguez-Rodrigo and Barba, 2007). These taphonomic characteristics are clearly suggestive of a very low competition setting, incompatible with an open-vegetation setting and similar to what is documented in riparian wooded habitats in modern savannas (Blumenschine, 1989; Domínguez-Rodrigo, 1996). This taphonomic inference is thus supported by the paleoenvironmental reconstruction of the site shown in the present work.

Conclusions

The FLK N archaeological site was located on a low-relief ridge on the broad lake margin of Paleolake Olduvai. The relief was probably not more than 1 m relative to the surrounding landscape, but it appears to have been a better-drained site that allowed the flourishing of dense woody vegetation such as thicket-woodland or forest. Woody plants and sedges occurred in the surrounding lowland (~15,000 m²), that had wet ground and standing water kept moist by seepage from groundwater-fed springs and seeps. Water appears to have come up along fault lines (FLK Fault and Zinj Fault). The freshest water and thus likely fastest flowing was associated with the Zinj Fault, whereas water seeped more slowly from the FLK Fault and experienced more evaporation. Phytoliths and pollen data in conjunction with the paleoenvironmental data indicate what appears to have been an "oasis" on this lake-margin floodplain which elsewhere supported grassland with scattered trees. This woody ecological niche may have persisted up to 15,000 yr at the end of upper Bed I time, providing the opportune setting for what appears to be a site with attraction for both carnivores and hominins.

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