Geochronology and physical context of Oldowan site formation at Kanjera South, Kenya.

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Abstract

Oldowan sites in primary geologic context are rare in the archaeological record. Here we describe the depositional environment of Oldowan occurrences at Kanjera South, Kenya, based on field descriptions and granulometric analysis. Excavations there have recovered a large Oldowan artefact sample as well as the oldest substantial sample of archaeological fauna. The deposits at Kanjera South consist of 30 m of fluvial, colluvial, and lacustrine sediments. Magneto- and bio-stratigraphy indicate the Kanjera South Member of the Kanjera Formation was deposited between 2.3 and 1.92 million years ago (Ma), with 2.0 Ma being a likely age for the archaeological occurrences. Oldowan artefacts and associated fauna were deposited in the colluvial and alluvial silts and sands of Beds KS-1 to KS-3, in the margins of a lake basin. Field descriptions and granulometric analysis of the sediment fine fraction indicates sediments from within the main archaeological horizon were emplaced as a combination of tractional and hyperconcentrated flows with limited evidence of debris flow deposition. This style of deposition is unlikely to significantly erode or disturb the underlying surface and therefore promotes preservation of surface archaeological accumulations. Hominins were repeatedly attracted to the site locale, and rapid sedimentation, minimal bone weathering, and an absence of bone or artefact rounding further indicate that fossils and artefacts were quickly buried.

1. Introduction

The appearance of Oldowan sites by 2.6 million years ago (Ma) reflects an important adaptive shift in hominin evolution. Stone artefact manufacture coupled with large mammal butchery and novel food and lithic transport and discard behaviours led to some of the oldest accumulations of archaeological debris (Potts, 1991; Plummer, 2004). Whereas Oldowan sites are known between ca. 2.6 – 1.7 Ma from East and South Africa and from North Africa and Georgia as well (Plummer, 2004), our understanding of the behavioural complexes leading to site formation remains rudimentary at best. In part this is because very few sites include both sizable artefact samples and well-preserved archaeological fauna. Moreover, it is sometimes unclear to what degree the associated fossil and artefact assemblages reflect on-site hominin activities, mixing of unrelated behavioural traces by geological processes, or palimpsests of activity traces from different taxa (e.g., hominins and carnivores) (Dominguez-Rodrigo, 2009).

At ca. 2.0 Ma, the site of Kanjera is particularly significant: Its Oldowan lithic and zoo archaeological assemblages are among the oldest and most substantial known and both record novel behaviours in an open habitat different from other, more wooded Oldowan sites (Table 1; Bishop *et al*., 2006; Plummer *et al*., 1999; Plummer & Bishop, 2016; Oliver *et al.*, submitted).Hominins were repeatedly attracted to the site locale and alluvial and colluvial deposition resulted in Oldowan artefact and fossil accumulations in an approximately 3 m thick sequence. In contrast to other Oldowan sites (e.g., FLK-Zinjanthropus, Olduvai Gorge) the Kanjera South assemblages document a suite of hominin behaviours that were not ephemeral, but persisted over time. Here we describe the geochronology and depositional context of the Oldowan site complex at Kanjera South, southwestern Kenya, focusing on the lithology and depositional history of the Kanjera South Member. In particular, new granulometric analyses have refined our previous understanding of the geological processes that formed Kanjera South and document that this Oldowan locality provides a reasonably unaltered record of hominin behaviour.

***************INSERT TABLE 1 NEAR HERE*****************

2. Physical setting

The early Pleistocene Oldowan occurrences at Kanjera South (0°20’24” S, 34°32’16” E) are found on the northern margins of the Homa Mountain Carbonatite Complex, Homa Peninsula, southwestern Kenya (Figure 1) (Le Bas, 1977). Homa Mountain is located on the southern shores of the Winam Gulf, a northeastern extension of Lake Victoria that lies in the fault-bounded Nyanza Rift system (Saggerson, 1952). Volcanic activity associated with the mountain began with doming of the central portion of the edifice in the late Miocene and shifted to peripheral vents during the Pliocene and Pleistocene (Le Bas, 1977; Saggerson, 1952). Today, the heavily eroded edifice of Homa Mountain is 1754 m high, approximately 600 m above the level of Lake Victoria. The mountain’s lower slopes are incised by a radial drainage system exposing late Miocene through Recent sediments (Kent, 1942; Ditchfield *et al*., 1999; Pickford, 1984). Evergreen forest and bushes cover portions of the upper slopes undisturbed by human activity.

The history of paleoanthropological research on the peninsula is summarized in Behrensmeyer *et al*., (1995), Ditchfield *et al*., (1999), Pickford, (1984), and Plummer & Potts, (1995). Fossiliferous deposits outcrop at Kanjera in three areas, termed the Northern, Middle and Southern Exposures (Figure 1). Initially, deposits in the Northern and Southern Exposures were thought to be equivalent, though the stratigraphic framework was largely based on observations made in Kanjera North (Oswald, 1914; Kent, 1942; Pilbeam, 1974; Pickford, 1987). As more attention was paid to the stratigraphy of the Southern Exposures some differences in composition between the deposits in the north and south emerged, and separate bed definitions were devised for each area (Behrensmeyer *et al*., 1995). Further work (Ditchfield *et al*., 1999; Plummer *et al*., 1999) indicated that no lithostratigraphic correlation existed between the North and South, and that the Southern Exposure~~s~~ sequence largely or entirely predates deposition in the North. Deposits in the north and south were provisionally designated Kanjera Formation (N) and Kanjera Formation (S), respectively (Ditchfield *et al*., (1999). The Kanjera North exposures consist of a series of low mounds of less than 3 m vertical relief and include the type site of *Theropithecus oswaldi* and the discovery site of some controversial anatomically modern human fossils by L. S. B. Leakey (Leakey, 1935; Behrensmeyer *et al*., 1995; Plummer & Potts, 1995). Magneto- and biostratigraphy suggest that deposition of the Kanjera Formation (N) began in the mid to late early Pleistocene and continued into the middle Pleistocene (Behrensmeyer *et al*., 1995). Sediments were deposited at the margin of a small playa or lake, in fluvial, lake flat, and lacustrine settings.

The Kanjera South deposits outcrop approximately 600m south of the Kanjera North location in a small (50,000 m^2), eastward-facing amphitheater reaching approximately 14 m above modern Lake Victoria (Behrensmeyer *et al*., 1995).

3. Geologic context of Oldowan occurrences

The Kanjera Formation is located on the northern flanks of the Homa Mountain massif. The country rocks of the Homa Peninsula consist of the Bukoben and Nyanzian metavolcanics and other high-grade metamorphic rocks (Saggerson, 1952; Le Bas, 1977). The emplacement of the Homa Mountain carbonatite system resulted in extensive fracturing and fenetization of these country rocks. The Plio-Pleistocene sediments are distributed radially around the Homa Mountain edifice and unconformably overlie Miocene sediments of the Kanam Formation in some areas.

The Kanjera Formation is exposed regionally at Kanjera~~,~~ in the ~~Southern,~~ Northern, ~~and~~ Middle and Southern Exposures (Behrensmeyer *et al.*, 1995; Plummer *et al.*, 1999, Ditchfield *et al*., 1999). The oldest units, Beds KS-1 to KS-5, make up the Kanjera South Member and are exposed at the Kanjera South locality (Figure 1). They have been the subject of extensive archaeological enquiry (Plummer *et al*., 1999; Plummer, 2004; Ferraro, 2007; Braun *et al*., 2008~~;~~,2009; Plummer *et al*., 2009; Ferraro et al., 2013; Lemorini et al., 2014; Plummer & Bishop, 2016). These beds are gently dipping to the north and are affected to a minor extent by normal faults down-stepping to the north, and associated minor folding. The Kanjera South Member is overlain unconformably by the beds of Kanjera North Member (Beds KN1-KN5), which also dip northwards but are more intensively deformed by faulting associated with the Winam Gulf graben. These members were previously informally referred to as Kanjera Fm (S) and Kanjera Fm (N) (Plummer *et al.*, 1999). Both Kanjera South and Kanjera North Members are unconformably overlain by the Kanjera Middle Exposure Member (KME-1 to KME-3), which represents a west-to-east directed alluvial fan sequence erosive into both underlying members.

3.a. Kanjera Bed Descriptions and Granulometric Analysis

The lithological sequence of the Kanjera South Member consists of colluvially and, to a lesser extent, alluvially reworked pyroclastic deposits and lacustrine clays, capped by a local volcanic sequence related to a late, peripheral, parasitic vent from the Homa Mountain Volcanic Complex. It has yielded archaeological occurrences from the top of Bed KS-1 through to the lower part of Bed KS-3.

The base of the Kanjera South Member, Bed KS-1, is a thick, poorly bedded, pyroclastic deposit. This is at least 4m thick and its base has not been reached in any of the excavations or geological trenches. The lowest visible part of this bed consists of very poorly sorted agglomerate with clast sizes ranging from granule to large boulders (in excess of 1m diameter). These clasts are strongly matrix supported in a fine sand to silt grade micaceous matrix and clasts are largely sub-rounded, with a tendency for the smaller pebble- to granule-size clasts to be more angular. The clast population is dominated by igneous rock types associated with the Homa Mountain volcanic complex. These range from coarse-grained ijolites to fine grained carbonatites. The clast population also includes a significant proportion of fenetized, fine grained, Nyanzian lavas and other pre-Cambrian basement lithologies. This lower part of KS-1 shows little internal stratification whereas the upper part is more regularly bedded. This upper part shows discrete beds up to 50cm thick, often delineated by pebble to granule stringers at the base of the bed, which tend to be planar and weakly erosive into the underlying unit. These upper parts of Bed KS-1 show weak to moderate pedogenic alteration of the pyroclastic parent material with occasional *in situ* soil carbonates preserved.
The overlying bed, KS-2, has a poorly-defined base and is often gradational from the upper part of KS-1. This bed is a moderately pedogenically altered and micaceous clay to gravel deposit dominated by silty sand. KS-2 contains common granule to pebble grade clasts of local igneous rock frequently arranged as laterally discontinuous stringers, often only a single pebble or granule thick and typically extending laterally only a few centimeters. At several horizons in the upper part of KS-2 there are thicker pebble conglomerates that form laterally discontinuous lenses. These conglomerates are matrix- to weakly clast-supported and dominated by pebble-size clasts of local igneous rock types. Pebbles are sub-angular to sub-rounded and show no clear imbrication. The conglomerate lenses vary from 5cm to 30cm thick; they lack any real channelization and show only very weakly erosive bases or no evidence of erosive bases. Lenses occasionally show preferential carbonate cementation relative to the surrounding finer grained material. The alluvial architecture of this unit comprises of broad, shallow, weakly defined channels, or sheet flood type structures (Blair, 1999). Deposition via hyper-concentrated,

tractional and mudflow processes are inferred. Within KS-2 palaeosol development occurs at several horizons but is spatially discontinuous and shows only moderate to weak development.

Bed KS-3 varies from a silt-rich, fine-grained sand to medium sand, with an often strongly bioturbated base. The bioturbation is frequently accompanied by preserved large mammal footprints and, along with other soft sediment deformation features, points to a wetter environment of deposition. KS-3 also shows moderate- to well-developed palaeosols with *in situ* carbonate rhizoliths as well as other pedogenic carbonate nodules. At Excavation 2, towards the northern part of the Kanjera South exposures, a channel facies of KS-3 is exposed. This displays clear cross bedding with mean flow directions to the north in a moderately sized (at least 3m width) asymmetric channel, the base of which is marked by a thin, discontinuous pebble lag marking an erosive surface into the underlying KS-2.

Bed KS-4 is a massively bedded grey to brown, plastic, poorly sorted clayey silt with occasional pedogenically altered horizons with weak carbonate nodule formation and root marks. It contains very few terrestrial fossils, but fish teeth, otoliths, and fresh water gastropods are relatively common. No archaeological materials have been recovered from bed KS-4.

Bed KS-5 consists of beds of red brown, poorly sorted silty clay showing signs of moderate pedogenesis alternating with bands of clast-supported pebble conglomerates up to 30 cm thick. It has a gradational base and its top has not been observed at Kanjera South. In the southern part of the outcrop the conglomerate beds become more restricted within steep sided channel features up to 1 m thick and 2.5 m wide. These channels are filled with a strongly matrix-supported, well-cemented, pebble conglomerate dominated by clasts fine grained carbonatite lavas and scoria. These channel features are laterally traceable to the south where they are seen to pass into bedded agglomerates associated with a local carbonatite vent sequence (see below).

In the southern part of the Kanjera South exposures the sedimentary sequence is overlain by pyroclastic deposits and minor carbonatite lavas from a local, late stage, peripheral vent associated with the Homa Mountain volcanic complex. These include several feeder dykes to this vent. These dykes cross cut the Kanjera South Formation (beds KS-2 to KS-4) below the main outcrop of the volcanic sequence. The agglomerate beds associated with this vent interdigitate with the conglomerates of KS-5 to the west of Excavation 1.

In the northern part of the Kanjera South exposures the sequence is truncated by an erosive unconformity, which is overlain by the conglomerates of the Middle Exposures Member. Figure 3 is a fence diagram showing representative logs of the above lithological units from geological trenches and archaeological excavations in the Kanjera South area.

4. Granulometric analysis

Particle size analysis (PSA) has long been an established technique in reconstructing the, transport processes, depositional mechanisms and depositional environments of sediments (Liu et al., 2014; Clarke et al., 2014; Amireh, 2015; Hassan, 1978; Friedman, 1979; Le Roux & Rojas, 2007). Due to the ubiquitous nature of sediments, the application of PSA spans an array of environmental settings (de Haas et al., 2014; Dill & Ludwig, 2008; Dinakaran & Krishnayya, 2011; Bement et al., 2007; Guan et al., 2016) and time periods (Amit et al., 2007; Yin et al., 2011; Wang et al., 2015; Schillereff et al., 2015; Lekach et al., 1998; Houben, 2007; Gillies et al., 1996). PSA has aided the current research by providing insights into the sedimentary environments and palaeohydrology at Kanjera South, allowing existing palaeoenvironmental reconstructions to be refined.

4.1. Methodology

53 spot samples were taken in excavations and geological trenches from beds KS1 to 5. Samples were subject to chemical pre-treatment outlined by (Konert & Vandenberghe 1997) to isolate discrete particles and provide evenly dispersed suspension (Liu et al. 2014). Carbonates were not removed using hydrochloric acid, as these were suspected to make up a large proportion of the samples and be part of the original deposition. Analysis of samples was undertaken using laser diffraction, with each sample run 5 times to ensure reproducibility. Laser diffraction is limited to the analysis of the fine fraction (<2mm); this fraction will be discussed herein. A detailed overview of the use of laser diffraction is given by Blott et al. (2004). The software package 'GradiStat' was used to analyse the results from particle size analysis, as well as to calculate textural parameters in phi units. A detailed overview of the package and its uses is provided by (Blott & Pye 2001).

4.2. Results

Particle size distributions are presented as size class divisions, due to the occurrence of polymodal sediments (Figure 4); bed contacts are excluded from this representation. In KS1, samples are composed of clayey silts with subordinate very fine sands. They are characterised by a fine skew and poor/very poor sorting, with almost all of the sediment belonging to the suspension load (Visher 1969). In KS2 there is a coarsening of sediments to silty sands, which are noticeably more poorly sorted than adjacent beds. Samples are very poorly sorted and fine skewed, with higher percentages of coarse sand, suggestive of a more significant saltation load during this period of deposition. Samples are also increasingly polymodal. KS3 sees a fining trend from KS2, with sediments consisting of silty sand and sandy silts more likely to have been transported through suspension. Poor to very poor sorting and a fine skew continue to define sediments in KS3. Sediments continue to follow a fining trend into KS4 with very poorly sorted and fine skewed clayey silts. The fine fraction of KS5 shows similar characteristics, with the exception of some samples that are composed of silty clays as well as clayey silts. Sediments remain poorly/very poorly sorted. With the reduction of coarser grain sizes in this fine grained units of this bed, some samples lack any skew, whilst some maintain a fine skew.

*****INSERT FIGURE 4 DISPLAYING PARTICLE SIZE DISTRIBUTIONS HERE******

5. Environmental interpretation

The sedimentology and lithology of the Kanjera South Formation provide a record of the palaeoenvironments of its deposition. Previous interpretations of the Kanjera depositional environments are shown in Table 2. The analysis presented below draws upon these previous studies and adds further field and laboratory analysis, including the previously discussed granulometric analysis of the matrix sediment (see Table 2 and Figure 4).

***************INSERT TABLE 2 NEAR HERE*****************

The lower part of KS-1 possibly represents the deposits of one or more relatively large flows of remobilized pyroclastic material, likely as lahars (volcanic debris flows) based on the abundance of clays and silts, as well as its very poor sorting and fine skew, in addition to the presence of large clasts and boulders of a wide variety of Homa Mountain igneous lithologies. These most probably moved from the Homa Mountain complex in the south towards a depositional center in the north related to the Winam Gulf graben. These lower parts of KS-1 show little internal stratification and no pedogenic development and likely represent rapid deposition. The upper parts of KS-1, which lacks the coarse conglomerate component (boulder-grade material), and includes weak pedogenic development, represents intermittent reworking of the pyroclastic flow deposits probably by ephemeral streams running across the landscape. KS-2 further develops this latter style of deposition with more widespread and better-developed pedogenesis, indicating wider temporal spacing between depositional events. Unconfined channel structures (with weak erosive, weakly developed channel base structures) very poor sorting of the <2mm fraction (poorly sorted grain size assemblages in the >2mm fraction), multi-modality and fine-skew indicates deposition is likely to have been dominated by intermittent hyperconcentrated-to-mudflow events of an unconfined nature (Pierson, 2005). Such flow events would have been separated by periods of landscape stability with periods of pedogenic development, characteristic of alluvial fan and pediment/slope environments. This is important to the interpretation of archaeological remains deposited in KS-2, as this style of deposition is less likely to erode the underlying surface, due to the relatively viscous nature and low shear stress bases (Pierson, 2005). This promotes preservation of surface archaeological accumulation, as surface objects are buried rather than eroded (de la Torre *et al.*, 2017; Stanistreet *et al.*, 2018). In addition to this, flow hiatuses may have been characterised by aeolian deposition and reworking of sediment, which may have been subsequently reworked. Such reworking may account for the abundance of fine sediment, as well as the multimodal nature of grain size distributions (Vandenberghe*et al.*, 2013). Overall, the depositional environment of KS-2 is compatible with an alluvial plain setting.

KS-3 sees the transition to a wetter depositional environment reflected in the style of pedogenic alteration and preservation of soft sediment deformation features (especially large mammal pedoturbation), as well as the abundance of clays/silts and a very fine skew in the sediment. There is evidence of at least one channel in the area, as seen from the sequence at Excavation 2. This channel was at least 1 m deep and 3 m wide and preserved the partial skeleton of a hippopotamid associated with artefacts. KS-4 represents a continuation of this wetting trend as lake margin deposits transgressed from north to south over the area. Despite this, the lake system was at least periodically dry enough for minor palaeosol development to take place within at least two horizons in this unit.

Bed KS-5 represents a return to terrestrial conditions following regression of the lake, possibly mediated by local uplift associated with the activity of the nearby Kanjera South volcanic vent system.

The lahar deposit that defines the lowermost known extent of KS-1 would have been significant in the local area and perhaps beyond. Because the main unstratifed body of the flow is at least

3m thick, it likely destroyed all standing vegetation in its path and modified some aspects of local topography. The main archaeological horizon concentrated in KS-2 and uppermost KS-1 accumulated during the interval following the emplacement of the lahar deposits at the base of bed KS-1 and before the lake margin transgression across the area at the base of bed KS-4. Stable isotopic analysis of pedogenic carbonates from these archaeological strata at Kanjera South show a uniformly C4 grass-dominated signal that is further supported by the taxonomic and isotopic analyses of the numerous mammalian fossil remains recovered from the site (Plummer *et al.*, 1999; Plummer *et al.*, 2009). Kanjera South thus may have been a particularly attractive locality for hominin activity during that time, with lake margin grassland on at least seasonally moist soils supporting an abundant local fauna, and ephemeral streams supporting patches of plants producing underground storage organs (Lemorini *et al.*, 2014).

6. Geochronology

A precise geochronology for the Kanjera South deposits is somewhat difficult to construct, due in part to the resistance to known dating techniques of the igneous material recovered so far. Repeated attempts to date overlying volcanics using Ar-Ar methods have been unsuccessful. However, a combination of palaeomagnetic and biostratigraphic studies using the abundant mammalian fauna allow us to delimit the age of the archaeological deposits. The proboscidean *Deinotherium* sp., the suids *Metridiochoerus modestus* and *M. andrewsi,* as well as the extant genus of equid *Equus* have all been recovered. The earliest African appearance of *Equus* dates to 2.3 Ma as does the First Appearance Datum (FAD) for *M. modestus* (Cooke, 2007). *M. andrewsi* is known from 3.36 Ma – 1.7 Ma elsewhere in Africa and *Deinotherium* sp. is known from deposits older than 1.5 Ma. These taxa indicate that archaeological materials were deposited between 2.3 -1.7 Ma. Moreover, the Olduvai Subchron (1.922 – 1.775 Ma, Singer 2014) has been detected in the sediments of Beds KS-4 and KS-5 (Ditchfield *et al*., 1999). In Ditchfield et al. (1999: 141) the Olduvai Subchron was mistakenly identified as beginning in KS-5, as the label for KS-4 was missing from Fig. 8. This figure should have shown Bed KS-4 extending from just below paleomag sample KJS 51 to about 20 cm above paleomag sample KJS 45. Thus, normal polarity paleomag samples KJS 45-56 are from KS-4, demonstrating that the Olduvai Subchron extended from KS-4 across it's contact with basal KS-5. The underlying archaeological occurrences in Beds KS-1 to KS-3 must therefore predate the base of the Olduvai subchron at 1.92 Ma, yielding a date of between 2.3 and 1.92 Ma for hominin activity. Given the rapidity of deposition, it seems likely that the archaeological occurrences are closer to the younger end of this time interval, with an approximate age of ~2 Ma.

7. Analysis of site formation

In any discussion of archaeological site formation the central question to be addressed is the extent to which artefacts and fossils are in primary depositional context. The answer to this question determines the types of behavioural inferences that can be drawn from study of the archaeological material. At Kanjera South it is impossible to determine whether the sedimentary matrices were deposited primarily by alluvial and/or colluvial action given the lack of sedimentary structures in uppermost KS2. Field sedimentological observations coupled with granulometric analyses of the matrix indicate the most likely environment of formation for KS-2 is an alluvial fan/pediment. Deposition is characterized by hyper-concentrated (ss. Pierson, 2005; de la Torre *et al.*, 2017) and tractional, unconfined flow events (Blair, 1999). It is possible given the fine-grained nature, fine-skew and multi-modality that sediments were partly deposited via aeolian processes (Vandenberghe *et al.*, 2013). Sedimentary structures are absent due in part to *in situ* breakdown of volcanic materials from the Homa Mountain complex, which are altering into clays. Where bedding structures are present and not obliterated by subsequent pedogenesis they lack significant channelisation and thus tend to point more towards unconfined sheet flow-like processes. The planar to undulating, unchannelised nature of pebbly lags at the base of some beds also supports this interpretation. Within the archaeological strata, most of the artefacts and bones are outsized clasts compared to the enclosing sediment (Plummer *et al*., 1999). The general low energy/fine-grained nature of the facies, coupled with evidence of mudflow to hyperconcentrated flow and hyper-concentrated flows (notwithstanding minor conglomeratic lenses in KS-2), indicates that depositional processes buried an *in situ* accumulation of artefacts and fossils. The general state of the archaeological materials, which show little weathering or rounding, preserve good surface and edge detail, and include bones with a range of hydraulic potentials strongly supports this interpretation (Plummer *et al.*, 1999; Ferraro *et al.*, 2013; Lemorini *et al.*, 2014). Finally, the presence of thousands of non-identifiable bone fragments less than 2 cm in length (Ferraro, 2007), which would likely have been winnowed away under a high energy flow regime, also argues against the bone and artefact assemblages being formed through hydraulic activity. That these small fragments are not being transported from elsewhere is indicated by their frequent association with larger bones bearing evidence of hammerstone percussion. Given the above and taking into account the vertical distribution of materials, deposit depths, and estimated rates of sedimentation, deposition likely occurred over a period of decades to centuries per bed burying stone tools and faunal remains at or very near their place of discard.

8. Conclusions

In summary, this paper presents the geological setting and lithostratigraphic descriptions of the herein designated Kanjera South Member of the Kanjera Formation. Archaeological traces of Oldowan hominin behaviour have been recovered primarily from the upper part of Bed KS-1 through to the lower part of Bed KS-3, with a significant concentration in unit KS-2. Analysis of the sedimentary facies sequence and stable isotopic analysis of pedogenic carbonates within the archaeological sequence, point to a grass-dominated relatively low-slope environment, which formed relatively rapidly on top of earlier lahar deposits. There is a wetting trend from KS-1 to KS-4, possibly indicating that the lake margin was moving progressively closer through time. Traces of hominin activity in the area cease as lake facies transgressed from north to south across the site as seen in Bed KS-4. Although there are weak soil horizons within the lake deposits in KS-4 indicating at least periodic retreat of the lake, these have yielded no archaeological materials. Granulometric analyses of the sediments indicate a sedimentary regime of hyperconcentrated flows with subordinate mudflows, which would not have significantly eroded or altered the surface on which they were deposited (Pierson, 2005; de la Torre *et al.*, 2017). It is notable that a similar depositional environment was recognized in Bed I Olduvai Gorge, Tanzania where this interpretation has also been applied (Stanistreet, 2012). The sedimentology and site formation processes of the archaeological strata at Kanjera South support the interpretation that the Oldowan assemblages represent a primary context accumulation from which behavioural inferences can be reliably drawn.

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References

Amireh, B.S. (2015). Grain size analysis of the Lower Cambrian-Lower Cretaceous clastic sequence of Jordan: Sedimentological and paleo-hydrodynamical implications. *Journal of Asian Earth Sciences*. 97 (PA). pp. 67–88.

Amit, R., Lekach, J., Ayalon, A., Porat, N. & Grodek, T. (2007). New insight into pedogenic processes in extremely arid environments and their paleoclimatic implications-the Negev Desert, Israel. *Quaternary International*. 162-163. pp. 61–75.

Behrensmeyer, A. K., Potts, R., Plummer, T. W., Tauxe, L., Opdyke, N., & Jorstad, T. 1995. The Pleistocene locality of Kanjera, Western Kenya: Stratigraphy, chronology and paleoenvironments. *Journal of Human Evolution* **29**, 247-274.

Bement, L.C., Carter, B.J., Varney, R.A., Cummings, L.S. & Sudbury, J.B. (2007). Paleo-environmental reconstruction and bio-stratigraphy, Oklahoma Panhandle, USA. *Quaternary International*. 169-170 (SPEC. ISS.). pp. 39–50.

Bishop, L. C., Plummer, T. W., Ferraro, J. V., Braun, D., Ditchfield, P. W., Hertel, F., Kingston, J. D., Hicks, J., & Potts, R. 2006. Recent research into Oldowan hominin activities at Kanjera South, Western Kenya. *African Archaeological Review* **23**(1), 31-40.

Blair, T. C. 1999.Sedimentary processes and facies of the water laid Anvil Spring Canyon alluvial fan, Death Valley, California. *Sedimentology* **46**(5), 913-940.

Blott, S.J. & Pye, K. (2001). Gradistat: A grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surface Processes and Landforms*. 26 (11). pp. 1237–1248.

Blott, S. J., Croft, D. J., Pye, K., Saye, S. E., & Wilson, H. E. (2004). Particle size analysis by laser diffraction. Geological Society, London, Special Publications, 232(1), 63–73.

Braun, D. R., Plummer, T., Ditchfield, P., Ferraro, J. V., Maina, D., Bishop, L. C., & Potts, R. 2008.Oldowan behavior and raw material transport: perspectives from the Kanjera Formation. *Journal of Archaeological Science* **35**, 2329-2345.

Braun, D. R., Plummer, T., Ferraro, J. V., Ditchfield, P., Bishop, L. C. 2009. Raw material quality and Oldowan hominin tool stone preferences: evidence from Kanjera South, Kenya. *Journal of Archaeological Science* **36**, 1605-1614.

Clarke, D.W., Boyle, J.F., Chiverrell, R.C., Lario, J. & Plater, A.J. (2014). A sediment record of barrier estuary behaviour at the mesoscale: Interpreting high-resolution particle size analysis. *Geomorphology*. 221. pp. 51–68.

Cooke, H. B. S. 2007. Stratigraphic variation in Suidae from the Shungura Formation and some coeval deposits. In *Hominin environments in the East African Pliocene*, (eds R. Bobe, Z. Alemseged, & A. K. Behrensmeyer), pp. 107-127. Dordrecht: Springer.

de Haas, T., Ventra, D., Carbonneau, P.E. & Kleinhans, M.G. (2014). Debris-flow dominance of alluvial fans masked by runoff reworking and weathering. *Geomorphology*. 217. pp. 165–181.

de la Torre, I., Albert, R. M., Macphail, R., McHenry, L. J., Pante, M. C., Rodríguez-Cintas, Á., Stanistreet, I. G., & Stollhofen, H. 2017. The contexts and early Acheulean archaeology of the EF-HR paleo-landscape (Olduvai Gorge, Tanzania). *Journal of Human Evolution*,

Dill, H.G. & Ludwig, R.R. (2008). Geomorphological-sedimentological studies of landform types and modern placer deposits in the savanna (Southern Malawi). *Ore Geology Reviews*. 33 (3-4). pp. 411–434.

Dinakaran, J. & Krishnayya, N.S.R. (2011). Variations in total organic carbon and grain size distribution in ephemeral river sediments in western India. *International Journal of Sediment Research*. 26 (2). pp. 239–246.

Ditchfield, P., Hicks, J., Plummer, T., Bishop, L. C., & Potts, R. 1999.Current research on the Late Pliocene and Pleistocene deposits north of Homa Mountain, southwestern Kenya. *Journal of Human Evolution* **36**(2): 123-150.

Domınguez-Rodrigo, M. 2009. Are all Oldowan sites palimsests? If so, what can they tell us of hominid carnivory? In E Hovers and DR Braun (eds.): *Interdisciplinary Approaches to the Oldowan*. Dordrecht: Springer, pp. 129-148.

Ferraro, J. V. 2007. Broken bones and shattered stones: on the foraging ecology of Oldowan hominins. Published PhD thesis. University of California Los Angeles, Los Angeles, California. ProQuest 3317002.

Ferraro, J. V., Plummer, T. W., Pobiner, B. L., Oliver, J. S., Bishop, L. C., Braun, D. R., Ditchfield, P. W., Seaman, J. W., Binetti, K. W., Seaman, J. W., Jr., Hertel, F., & Potts, R.2013. Earliest archaeological evidence of persistent hominin carnivory. *PLoS ONE*, **8**(4), e62174.

Flemming, B. W. 2007. The influence of grain-size analysis methods and sediment mixing on curve shapes and textural parameters: Implications for sediment trend analysis. *Sedimentary Geology***202**(3), 425–435.

Friedman, G.M. (1979). Differences in size distributions of population particles among sands of various origins. *Sedimentology*. 26 (6). pp. 859–862.

Gillies, J.A., Nickling, W.G. & McTainsh, G.H. (1996). Dust concentrations and particle-size characteristics of an intense dust haze event: Inland Delta region, Mali, West Africa. *Atmospheric Environment*. 30 (7). pp. 1081–1090.

Guan, H., Zhu, C., Zhu, T., Wu, L. & Li, Y. (2016). Grain size , magnetic susceptibility and geochemical characteristics of the loess in the Chaohu lake basin : Implications for the origin, palaeoclimatic change and provenance. *Journal of Asian Earth Sciences*. 117. pp. 170–183.

Hartmann, D. 2007. From reality to model: Operationalism and the value chain of particle-size analysis of natural sediments. *Sedimentary Geology***202**(3), 383–401.

Hassan, F.A. (1978). Sediments in Archaeology: Methods and Implications for Palaeoenvironmental and Cultural Analysis. *Journal of Field Archaeology*. 5 (2). pp. 197–213.

Houben, P. (2007). Geomorphological facies reconstruction of Late Quaternary alluvia by the application of fluvial architecture concepts. *Geomorphology*. 86 (1-2). pp. 94–114.

Kent, P. E. 1942.The Pleistocene beds of Kanam and Kanjera, Kavirondo, Kenya. *Geological Magazine* **79**,117–132.

Konert, M. & Vandenberghe, J. (1997). Comparison of laser grain size analysis with pipette and sieve analysis: a solution for the underestimation of the clay fraction. *Sedimentology*. 44 (3). pp. 523–535.

Le Bas, M. J. 1977.*Carbonatite-nephelinite volcanism: an African case history*. London: Wiley.

Le Roux, J.P. & Rojas, E.M. (2007). Sediment transport patterns determined from grain size parameters: Overview and state of the art. *Sedimentary Geology*. 202 (3). pp. 473–488.

Leakey, L. S. B. 1935.*The Stone Age races of Kenya*. Oxford: Oxford University Press.

Lekach, J., Amit, R., Grodek, T. & Schick, A.P. (1998). Fluvio-pedogenic processes in an ephemeral stream channel. *Geomorphology*. 23 (2-4). pp. 353–369.

Lemorini, C., Plummer, T. W., Braun, D. R., Crittenden, A. N., Ditchfield, P. W., Bishop, L. C., Hertel, F., Oliver, J. S., Marlowe, F. W., Schoeninger, M. J. & Potts, R. 2014. Old stones' song: use-wear experiments and analysis of the Oldowan quartz and quartzite assemblage from Kanjera South (Kenya). *Journal of Human Evolution***72**, 10-25.

Liu, B., Qu, J., Ning, D., Gao, Y., Zu, R. & An, Z. (2014). Grain-size study of aeolian sediments found east of Kumtagh Desert. *Aeolian Research*. 13. pp. 1–6.

Meyer, I., Davies, G. R., Vogt, C., Kuhlmann, H. & Stuut, J.-B. W. 2013. Changing rainfall patterns in NW Africa since the Younger Dryas. *Aeolian Research***10**, 111-123.

Oliver, J. S., Plummer, T. W., Bishop, L. C., &Hertel, F. *submitted 03/2018*. Bovid mortality patterns from Kanjera, Homa Peninsula, Kenya and FLK-Zinj, Olduvai Gorge, Tanzania: Habitat-mediated variability in Oldowan hominin hunting and scavenging behavior. *Journal of Human Evolution*.

Oswald, F. 1914.The Miocene Beds of the Victoria Nyanza and the geology of the country between the lake and the Kisii Highlands. *Quarterly Journal of the Geological Society of London*, **70**, 128-188.

Paterson, G. A. &Heslop, D. 2015. New methods for unmixing sediment grain size data. *Geochemistry, Geophysics, Geosystems***16**, 4494-4506.

Pickford, M. 1984. *Kenya Palaeontology Gazetteer*, *Western Kenya* (Vol. 1). Nairobi, Kenya: National Museums of Kenya.

Pickford, M. (1987). The geology and palaeontology of the Kanam erosion gullies (Kenya).*MainzerGeowis- senschaftlicheMitteilungen***16**, 209–226.

Pierson, T. C. 2005.Hyperconcentrated flow—transitional process between water flow and debris flow. In *Debris-flow hazards and related phenomena* (pp. 159-202).Berlin, Heidelberg: Springer.

Pilbeam, D. 1974.*Hominid-bearing deposits at Kanjera, Nyanza Province, Kenya*. Unpublished report.

Plummer, T. W., & Potts, R. 1995. The hominid fossil sample from Kanjera, Kenya: Description, provenance and implications of new and earlier discoveries. *American Journal of Physical Anthropology***96**, 7–23.

Plummer, T. W., Bishop, L. C., Ditchfield, P., & Hicks, J. 1999. Research on Late Pliocene Oldowan sites at Kanjera South, Kenya. *Journal of Human Evolution* **36** (2), 151-170.

Plummer, T. W. 2004. Flaked stones and old bones: Biological and cultural evolution at the dawn of technology. *American Journal of Physical Anthropology* **125** (S39): 118-164.

Plummer, T. W., Ditchfield, P. W., Bishop, L. C., Kingston, J. D., Ferraro, J. V., Braun, D. R., Hertel, F. & Potts, R., 2009. Oldest evidence of tool making hominins in a grassland-dominated ecosystem. *PLoS ONE*, **4**(9), p.e7199.

Plummer, T. W. & Bishop, L. C. 2016. Oldowan hominin behavior and ecology at Kanjera South, Kenya. *Journal of Anthropological Sciences***94**, 29-40.

Potts, R. 1991. "Why the Oldowan? Plio-Pleistocene tool making and the transport of resources." *Journal of Anthropological Research* **47** (2): 153-176

Saggerson, E. P. 1952. Geology of the Kisumu District. *Geological Survey of Kenya*, Report 21, 86pp.

Schillereff, D.N., Chiverrell, R.C., Macdonald, N. & Hooke, J.M. (2015). Hydrological thresholds and basin control over paleoflood records in lakes. *Geology*. (1). p. G37261.1.

Singer, B. S. 2014.A Quaternary geomagnetic instability time scale. *Quaternary Geochronology***21**(c), 29–52.

Stanistreet, I. G. 2012. Fine resolution of early hominin time, Beds I and II, Olduvai Gorge, Tanzania. *Journal of Human Evolution***63**(2), 300–308.

Stanistreet, I. G., Stollhofen, H., Njau, J. K., Farrugia, P., Pante, M. C., Masao, F. T., Albert, R. M., & Bamford, M. K. 2018. Lahar inundated, modified, and preserved 1.88 Ma early hominin (OH24 and OH56) Olduvai DK site. *Journal of Human Evolution***116**, 27–42.

Vandenberghe, D. A. G., Derese, C., Kasse, C. 2013. Late Weichselian (fluvio-) aeolian sediments and Holocene drift-sands of the classic type locality in Twente (E Netherlands): a high-resolution dating study using optically stimulated luminescence. *Quaternary Science Reviews* **68**, 96-113.

Visher, G.S. (1969). Grain Size Distributions and Depositional processes. *Journal of Sedimentary Research*. 39 (3). pp. 1074–1106.

Wang, J., Li, A., Xu, K., Zheng, X. & Huang, J. (2015). Clay mineral and grain size studies of sediment provenances and paleoenvironment evolution in the middle Okinawa trough since 17ka. *Marine Geology*. 366. pp. 49–61.

Weltje, G. J. 1997. End-member modeling of compositional data: Numerical-statistical algorithms for solving the explicit mixing problem. *Mathematical Geology***29**(4), 503-549.

Weltje, G. J. &Prins, M. A. 2003. Muddled or mixed? Inferring palaeoclimate from size distributions of deep-sea clastics. *Sedimentary Geology***162**(1-2), 39-62.

Weltje, G. J. &Prins, M. A. 2007.Genetically meaningful decomposition of grain-size distributions. *Sedimentary Geology***202**(3), 409-424.

Yin, Y., Liu, H., He, S., Zhao, F., Zhu, J., Wang, H., Liu, G. & Wu, X. (2011). Patterns of local and regional grain size distribution and their application to Holocene climate reconstruction in semi-arid Inner Mongolia, China. *Palaeogeography, Palaeoclimatology, Palaeoecology*. 307 (1-4). pp. 168–176

Bed	Description	Palaeoevnrionmental Interpretation
KS-1	Grey-brown silty, gravelly sand and sandy silt, with layers of hard $CaCO_3$ nodules. These preserve fine horizontal lamination and indicate post-depositional calcification. Clasts including granite, grey and red chert, some volcanic material and large biotites present in gravel associated with coarser sand. Some thin clayey silt beds in upper 1m. Bimodal grain size distribution of medium-grained sand and fine silt-clay	Deposition initially began as a flow of pyroclastic material from the Homa Mountain complex towards depocenter Nyanza Rift graben in the north. These deposits reworked by ephemeral streams running across the fan of the original pyroclastic flows. Possibly a near-shore lacustrine or wet floodplain environment
KS-2	~1.3m of orange and yellow-grey gravelly sand, with a thin patchy conglomerate. Contains fresh biotites, angular and rounded volcanic and basement clasts. Cross-stratification orientated 150-155^{o} (southeast). Variable cementation, locally very mottled with irregular limonitic staining	Fluvial channel fill, with deposition by anastomosing channels flowing with intermittent, diffuse, generally low energy flow regimes
KS-3	~60cm of homogeneous and massive light orange to yellow-grey sandy silt with some tuffaceous silt. Some horizontal orange mottling. Includes partial *Hippopotamus* skeleton. Ostracods and fish scales also present	Continuation of KS2, with a transition to a wetter depositional environment. Small channel present with more stable land surfaces
KS-4	~3.2m thick grey-green and brown clay, with some silty clay and occasional sandy clay in lower bed. Clays generally dense, homogeneous, calcareous and mottled, with occasional slickensides and soft patches of $CaCO_3$. Sandy clay channel feature 1.5m above the base, with root traces and reworked clay clasts. Irregular bedding contacts within the clays suggest pedobioturbation. Increased $CaCO_3$ in upper half of unit; this occurs as vertical patches and small nodules. Pedogenesis evidenced by vertical cracking, decreased homogeneity of clay, and abundant nodules. Ostracods and fish debris in lower parts of bed	Very-low energy lacustrine or swamp deposition. Periodic sub-aerial exposure with some sub-aqueous deposition. Clays deposited either during the transgression of a lake or during the formation of a wetland system
KS-5	~2-2.5m of brown clayey sandy gravel, with matrix-supported grains and pebbles. Some resistant $CaCO_3$ layers interbedded; abundant volcanic gravel and cobbles present in some of these. One limestone bed has plant stem and root moulds, whereas others are massive and caliche-like. Clayey sand and gravel beds generally massive and bimodal, with some grain-supported gravel lenses and abundant small $CaCO_3$ nodules throughout	Fluvial deposition with a variable energy regime combined with pedogenisis and stable landsurface development
KS-6	2m of brown clay, grading upward to light-grey mottled gravelly clay and capped by an irregular, massive $CaCO_3$ bed up to 40cm in thickness. Lower part has fewer $CaCO_3$ nodules than KS-5. Upper part of bed has patches of gravelly and sandy clay, which are dark grey and have yellow streaks and mottling. Relatively pure clay with no coarser clast components	Continuation of KS5. Wet conditions, possibly near a spring or other source of calcium-saturated water

Table 2. Summary of bed descriptions and environmental interpretations for the Kanjera South area based on observations in this study and previously published descriptions from Behrensmeyer *et al*., (1995), Ditchfield *et al*., (1999), and Plummer *et al*., (2009).

Bed	Total NISP	Macro-mammal NISP	Macro-mammal MNI	Principal fauna (%NISP, %MNI)	Artefacts
KS-1	982	975 (525)	25	Bovid (92.4, 72.0), Equid (4.4, 8.0), Suid (1.5, 8.0), Hippo (0.2, 4.0)	179
KS-2	2190	2153 (886)	40	Bovid (82.6, 67.5), Equid (11.6, 10.0), Suid (0.9, 5.0), Hippo (1.0, 2.5)	2533
KS-3	491	470 (172)	16	Bovid (77.9, 68.8), Equid (4.7, 6.3), Suid (0.6, 6.3), Hippo (14.0, 12.5)	171

Table 1: Excavated materials from Kanjera South. These samples were recovered predominantly from Excavation 1. ‘Total NISP’ refers to specimens that were collected with coordinate data. Thousands of non-identifiable bone fragments <2cm are not included in these counts, nor are fossils from the conglomeratic facies (CP levels of Plummer et al. 1999). Macro-mammals refers to animals weighing more than 5 kg. Macro-mammal NISP values are total sums, followed by the sum of specimens identified beyond Linnean class in parentheses. After Ferraro et al., 2013, Table 1.