



## Autochthonous anisotropy of archaeological materials by the action of water: experimental and archaeological reassessment of the orientation patterns at the Olduvai sites



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### ABSTRACT

Anisotropic patterns documented indirectly through M. Leakey's drawings of Olduvai archaeological sites have led to questions about the integrity of these sites. Most experiments on bone transport by water have been carried out using complete elements that do not replicate specimen bone breakage and size as documented in archaeological sites. In the present work, an experimental framework is provided using experimental proxies of archaeological assemblages. Results show that autochthonous assemblages affected by hydraulic processes can adopt anisotropy in their fabric. Archaeological comparisons between drawings and excavated sites at Olduvai stress the bias in Leakey's drawings of FLK Zinj and FLK North in Bed I. A large-scale open excavation recently carried out at TK (Bed II) exposes an area comparable in size to Leakey's excavations. Comparing the orientation patterns of this site to those reported by Leakey, shows how biased the drawing of the site is and how easily this can lead to misinterpretations of isotropy/anisotropy, with fatal consequences for the understanding of site formation processes.

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### 1. Introduction

The degree of post-depositional disturbance undergone by the Olduvai Bed I sites has been extensively discussed over the past three decades (see review in Domínguez-Rodrigo et al., 2007, 2012), but recent taphonomic and archaeological research has enabled scholars to reevaluate some of the previous interpretations. For example, the idea that the sites represent horizontal continuums of fossils and artefacts on a landscape (Blumenschine and Masao,

1991), was unsupported by recent research at FLK Zinj, when landscape archaeological work was carried out sampling the surrounding environment of this site and showing the sharp contrast in fossils and artefact density between the site and its paleo-landscape (Domínguez-Rodrigo et al., 2010a). Likewise, the interpretation of sites as palimpsests resulting from prolonged temporal periods of bone exposure and accumulation, based on the presence of fossils with several subaerial weathering stages (Potts, 1988), has been argued to be also an artefact of method, since more recent research has documented a virtual absence of bones exhibiting subaerial weathering (e.g., at FLK Zinj); rather, bones frequently exhibit chemical weathering caused by diagenesis (Domínguez-Rodrigo et al., 2007). Although some sites show clear taphonomic features suggesting that they are time-averaged palimpsests (e.g., FLK North), sedimentation processes were active enough for most

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bones not to have undergone any major subaerial weathering (Domínguez-Rodrigo et al., 2007).

Recent discussion of the post-depositional modifications of these sites caused by hydraulic processes has sparked debate as to whether the Bed I archaeological record was significantly altered, including some degree of allochthony (Benito-Calvo and de la Torre, 2011), or whether the assemblages were autochthonous and locally modified by sedimentation during the biostratigraphic (i.e., post-depositional) phase of the assemblage (Domínguez-Rodrigo et al., 2012). Recently, discarding their references to allochthonous processes, de la Torre and Benito-Calvo (2013) reiterate that the orientation patterns observed from Leakey's (1971) site maps are a clear indication of water processes being active during the formation of the Bed I and II sites. This debate has two crucial questions: one is whether such orientation patterns exist and are statistically sustainable; the other question is what, precisely, orientation indicates taphonomically. Current available geological evidence at FLK Zinj and FLK North shows that the assemblages were formed on paleosurfaces occurring on the top of a lake-formed clay deposit and overlaid by volcanic tuffs (Leakey, 1971; Domínguez-Rodrigo et al., 2012). No lithological or structural evidence of a channel has been reported for either site. Therefore, any purported influence of hydraulic disturbance on these assemblages must have occurred post-depositionally and not earlier during their depositional phase.

A substantial amount of actualistic research has been conducted with the goal of evaluating the degree of distortion introduced by the effect of water flows in Paleolithic archaeological assemblages prior to and during their sedimentation (see review in Petraglia and Potts, 1994). The variables most frequently used to infer hydraulic disturbance on lithic and bone remains are as diverse as the following:

1. Nature of depositional contexts (sedimentology): bed load contexts (gravel and sand) are more prone to high energy hydraulic modification of archaeological assemblages, while suspended load (silt and clay) contexts indicate low-energy settings.
2. Element size distribution: smaller elements are proportionally underrepresented in low/moderate to high-energy water flows (Schick, 1984; Domínguez-Rodrigo and García-Pérez, 2013).
3. Preferential orientation of archaeological items (Toots, 1965; Isaac, 1967; Voorhies, 1969).
4. Regular lack of refitting of archaeological items (Schick, 1984).
5. Long exposure near water currents (Petraglia and Nash, 1987).
6. The presence of rounding (polishing) and abrasion in a substantial part of any given bone assemblage that has been transported by water (Behrensmeier, 1975; Schick, 1984; Stein, 1987; Shipman and Rose, 1988; Fernández-Jalvo and Andrews, 2003; Thompson et al., 2011).
7. Differential anatomical representation according to bone type, with the most cancellous grease-bearing bones underrepresented (Voorhies, 1969).
8. A combination of animal size class and bone specimen size, with small specimens from small animals more prone to being underrepresented (Pante and Blumenshine, 2010).
9. A combination of quantitative variables in lithic assemblages based on average weight, a large-to-small artifact ratio and the relative representation of the fraction <50 g; those assemblages affected by water show high values for the former two variables and low values for the latter (Petraglia and Potts, 1994).

None of these variables taken individually is determinant of the energy of water flow velocity in archaeological sites. Both experimentally (Schick, 1984; Petraglia and Nash, 1987) and

archaeologically (e.g., Domínguez-Rodrigo et al., 2009), it has been shown that several assemblages in purported high-energy contexts, such as river channels, have been locally preserved with limited hydraulic modification. Element size distribution and refitting, although clearly biased by the transport energy of water flows, are initially determined by the degree of green bone breakage or stone tool knapping at the site. Rounding or polishing of bone is frequently difficult to differentiate macroscopically from carnivore digestion. Even when successfully differentiated by using magnification and microscopic criteria, rounding and polishing can also occur in detritic contexts where water circulates without the need for bones to be transported (Thompson et al., 2011).

Likewise, rounding of stone tools caused by hydraulic transportation can be difficult to differentiate from subaerial or diagenetic (chemical) weathering undergone by artefacts made from specific raw material types (e.g., volcanic rocks). Furthermore, rounding may also occur as a result of water flow over stationary items and not only by intensive water transport (Petraglia and Potts, 1994; Thompson et al., 2011). Voorhies' (1969) bone group types, although experimentally reflecting the degree of energy and transportation capability of water flows, have a rather limited applicability to the archaeological record because they were modeled using complete bones, which make up a small fraction of green-broken faunal assemblages at archaeological sites. In addition, Voorhies' scheme does not take into account that differential anatomical representation may initially have an anthropogenic origin, through selection and transport of specific parts, frequently discarding those lighter (and more easily winnowed by water) cancellous elements at the butchery site (Bunn, 1993, 2007). The combined use of animal size class and bone specimen size is also dependent on whether small animals were initially present at the site and, irrespective of animal size class, on the degree of bone fragmentation (*vide supra*), on the differential representation of elements and their resulting proportion of specimens after breakage (Pickering and Egeland, 2006) and the differential fragmentation documented in small versus larger animals (Yeshurun et al., 2007). Qualitative variables like those described by Petraglia and Potts (1994) for stone tools are also determined by the intensity of knapping at the site, the stage of the reduction sequence represented and the format types (large as in Acheulian versus small as in Oldowan stone assemblages). Other variables documented experimentally, such as the time of exposure, are difficult to assess archaeologically.

Last but not least, orientation is the most widely used variable to infer water sorting or rearrangement of archaeological materials. Experiments have shown that long axes of bones and, to a lesser extent, stone tools react to current direction and force by aligning parallel (preferentially) to the water flow (when completely covered by water) or transverse to it (more frequently when in shallow water or partially exposed to the surface) or forming criss-cross patterns (Toots, 1965; Isaac, 1967; Voorhies, 1969; Schick, 1984). However, the possibility that orientation could also have other causes has never been discarded. From a taphonomic point of view, this is important *vis-a-vis* producing reliable criteria to differentiate processes generating orientation of materials that could erroneously be interpreted as the result of winnowing by rivers or lakes. For example, trampling has been shown to produce movement of bones (Olsen and Shipman, 1988) and artifacts, predominantly in the same direction as the moving trampling agent, and sometimes transversal to it (see Figs. 4–7 of Eren et al. (2010)). Downslope gravity in the form of movement (with or without transportation) has also been argued to create differential movement of bones and re-oriented assemblages (Frostick and Reid, 1983; Petraglia, 1987; Bertran et al., 1997; Lenoble et al., 2008). Diagenetic processes, such as the plastic nature of clays through

saturation and drying, have also been shown to produce horizontal changes in orientation of some bones of up to 40° in very short intervals (one year) (Domínguez-Solera, 2010).

Despite all the available experimentation on the effects of water in lithic and bone assemblages, experiments have only rarely modeled water disturbance in archaeological assemblages (Schick, 1984). Most experiments have been conducted using complete bones (see *supra*), which behave differently from fragmented bones, since broken bones produce specimens with different sizes and shapes from complete elements. Transport of fragmented bones does not seem to be subject to the same bone structural density factors (Pante and Blumenschine, 2010) that determine transport of complete elements (Behrensmeier, 1975; Kaufmann et al., 2011). Schick (1984) experimentally reproduced assemblages with similar characteristics to archaeological assemblages, but did not pay special attention to bones. However, she noticed something important, which is that bones and lithics react very differently to hydraulic processes. In her experiments, bone recovery was “proportionate to that of smaller debitage (1–2 in maximum dimension)” (Schick, 1984: 102), showing that bones are far more sensitive to water disturbance than lithics. This indicates that criteria potentially useful for discerning the effect of water on lithic assemblages may not be useful for evaluating the same process on bones. Pante and Blumenschine (2010) made experiments with fragmented bones, but focused only on long limb bones.

The goals of the present work are to answer the following questions:

1. How much movement is required until a bone shows a preferred orientation and stabilization? How much time and energy is required for anisotropy to appear in any bone assemblage?
2. Do orientation forces influence specimen orientation along an A-axis that depends on its total length, or on a longitudinal axis that symmetrically divides the bone in two?
3. When using broken bones, do Voorhies' groups reflect the same type of hydraulic disturbance as documented with complete elements? How do shape and bone structure affect bone movement?

It has been shown that dry and wet bones have different transport potentials, with the latter being more easily transported (Coard, 1999). However, the difference in transport potential between both states is minimal (<1 cm/s) and was not supported statistically. Although some weathering was initially documented at FLK Zinj (Potts, 1988), a re-analysis of the bone remains showed that such weathering was marginal and diagenetic (Domínguez-Rodrigo et al., 2007). For this reason, the experiments reported in the present work emphasize the role of post-depositional disturbance on fresh bones, preserving their grease content, and unsaturated by water.

The results from the experiments presented here will be used to discuss what the orientation patterns recently documented at some of the Olduvai Bed I (FLK Zinj, FLK North) and Bed II (TK) sites (Benito-Calvo and de la Torre, 2011) represent in terms of site formation. For a description of these sites see Leakey (1971), Benito-Calvo and de la Torre, 2011, Domínguez-Rodrigo et al., 2012 and de la Torre and Benito-Calvo (2013). These purported anisotropic patterns have been reproduced from Leakey's (1971) published plans of the sites. An important omission in Leakey's (1971) plans is the third dimension; none of the Olduvai site maps reference objects that belong to the same vertical depth if they included all the elements from each level. Most Olduvai sites are deposits with variable depth, in which materials occupy variable vertical positions. This indicates substantial time-averaging and multiple depositional events. The lack of information in this regard, crucial

for the taphonomic understanding of the formation of these sites, was stressed by Domínguez-Rodrigo et al. (2007) and prompted the creation of the on-going Olduvai Paleoecology and Paleoanthropology Project (TOPPP). When looking at Leakey's maps, one really does not know what portions (levels) of these deposits are represented in several of them. Are the drawings a palimpsest of objects retrieved from different vertical depths of the deposit or the objects found in the densest spit or at the same horizontal depth? The only way to provide an answer to these questions is to re-excavate some of these sites and compare the resulting material distribution, orientation and recording with that provided by Leakey's maps. Here we show an example in this regard using data from TK (Upper Bed II) drawn from recent excavations of the site and its resulting mapping, which can be directly compared to Leakey's drawing of the site and the orientation patterns inferred thereof.

### 1.1. Method and sample

#### 1.1.1. How much bone movement is required until an assemblage shows a preferred orientation?

To address this question, in order to replicate bone patterns at sites, it is important to document how the individual different-sized fragments of each hammerstone-broken element, are post-depositionally transported away from the rest prior to documenting orientation patterns. Documenting the detachment and separation of these fragments involves controlling each fragmented element and the set of variables that intervene. For this reason, a first group of experiments involving few bones were carried out under artificial (flume) and natural (fluvial) conditions. Experiments in the flume also require a small number of bone fragments to avoid interference of bones in their transport caused by imbrications. The only questions addressed in these preliminary experiments were how much energy is necessary for bones to be oriented, and how long does that take. These initial experiments were followed by another set of experiments involving a larger sample of bones, including elements from each anatomical region. Bones in every experiment were initially placed in a star-shaped pattern following the 360° orientation of a circle, so that the assemblage showed a uniform distribution. This was further documented by applying circular statistics prior (in the flume) and after the experiment was conducted (see below).

Dry bones and wet bones (i.e., bones soaked in water) have been shown to behave differently under the same water flow (Coard, 1999; Coard and Dennell, 1995; Kaufmann et al., 2011). The present experiments were created with the goal of providing information for understanding site formation at the Olduvai Bed I sites. For this reason, we carried out our experiments using hammerstone-broken bones in which most bones were fresh. This yielded a realistic sample of the bones usually excavated at sites. The exposure of bones to water for hours allowed them to soak in water, so a combined effect of movement with dry and wet bones was tested. Water velocity was measured with a paddle velocimeter for the experiments in the flume and a digital flow probe for the experiment in the river. The symmetrical longitudinal axis (SLA) of each bone was taken as the orientation A-axis (Domínguez-Rodrigo et al., 2012). This contrasts with the polygon diameter (D) A-axis taken by Benito-Calvo and de la Torre (2011), considered as the maximum length of the specimen. In Experiments 1 and 3, measurements were taken on both types of A-axes to understand which one most accurately reflects the direction of the water current.

#### 1.1.2. Experiment 1

Ten experiments were carried out in a flume so that water depth and force could be homogeneously monitored. This is especially

relevant when conducting experiments under low-energy conditions. The flume was 6 m long, 30 cm wide and with a maximum depth of 10 cm. Since water was going to be used in low-energy conditions, bone disturbance was modeled with small bones. A total of 2 bones (a femur and a tibia) from a juvenile goat fragmented into 20 specimens was used. Water was run for only three minutes (given that bones stabilized in the first minute) in two forms: shallow and deep. Shallow flow implied running the flume with a 3 cm depth so that some small bones were covered by water and the bigger ones were exposed. Deep flow implied running the flume with water at 8 cm depth. Water velocity in both experiments was 15 cm/s. Five experiments were run for each depth type.

#### 1.1.3. Experiment 2

Flumes are artificial environments and bones may react differently from when experiments are conducted in real fluvial channels. Given that the base of the flume was plastic, a second experiment was conducted with the same bone sample as the previous experiment, plus 11 compact bones (1 calcaneum, 1 astragalus and 9 phalanges). Water velocity was measured at 25 cm/s. The experiment was conducted in a stream located at Patones de Arriba (Madrid) (Fig. 1). The base of the channel was composed of gravels and pebbles. The channel was modified to be

similarly sized to the flume used in the previous experiment, by creating side walls with clasts and pebbles (~8 cm deep and 36 cm wide, although in places depth was ~3 cm). Bones were completely covered by water. Five experiments were conducted in total. Each experiment lasted 15 min. In this experiment bones were oriented using their longitudinal A-axes only.

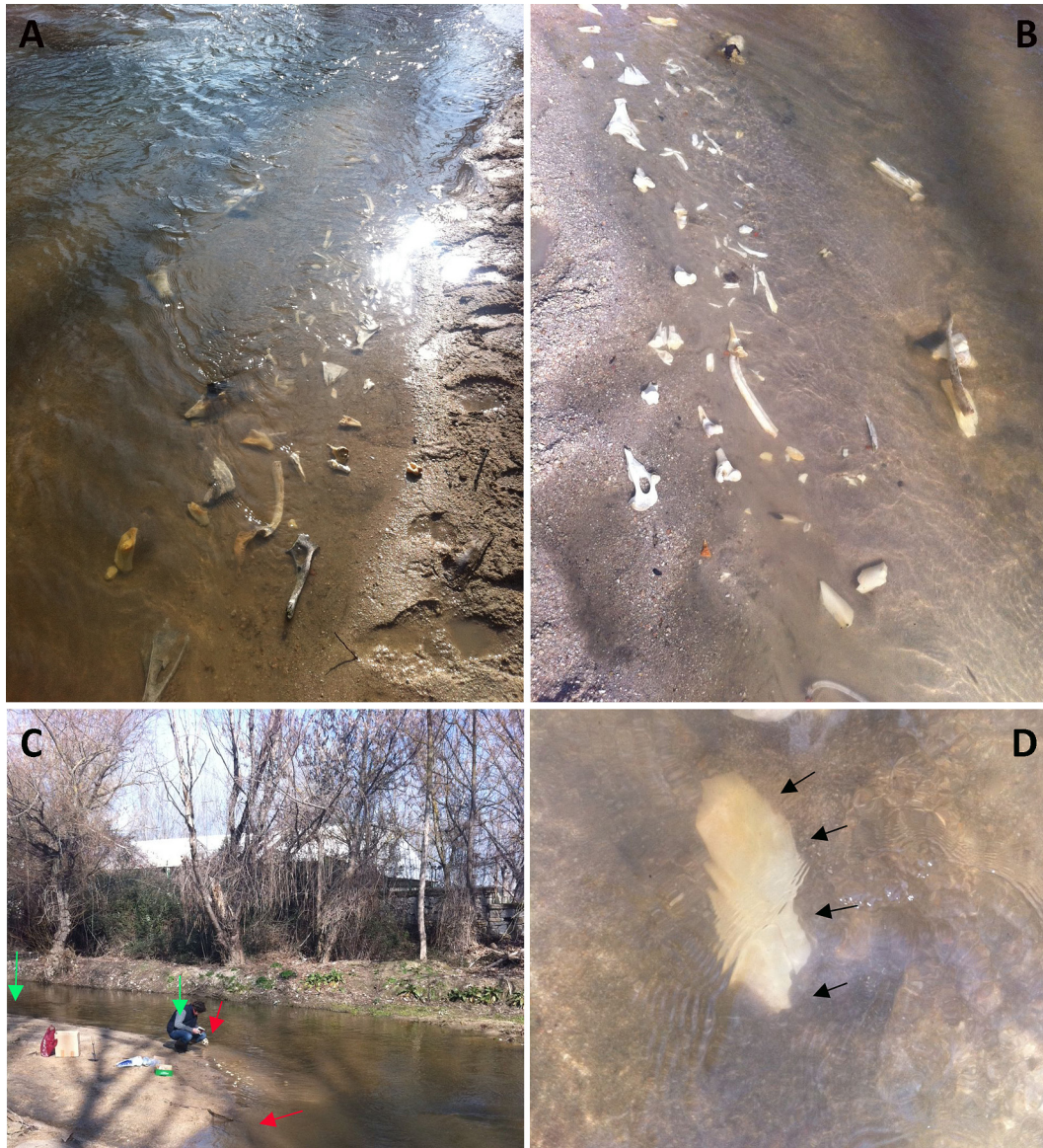
#### 1.1.4. Experiment 3

A third experiment involving a large sample (132 bones) was subsequently carried out in a bar inside the channel of the Manzanares river in Madrid (Fig. 2). Bones were from two goats (1 humerus, 3 femora, 4 tibiae, 7 tarsals, 3 carpals, 2 scapulae, 3 pelvises, 2 skulls, 1 mandible) representing small-sized animals, one deer (2 mandibles, 3 pelvises, 3 ribs, 2 scapulae), one horse (2 vertebrae, 1 rib, 1 humerus) and one cow (1 tibia, 1 rib, 1 femur), representing the large-sized animals. The sample is composed of 132 fragmented specimens (Tables 1 and 2). The composition per bone section is shown in Table 1. Each bone specimen was numbered so that its movement and orientation could be entered in a database including its dimensions and shape.

Bones were placed with random orientations inside the channel in two series. Series One involved placing the least dense specimens in the shallowest portion of the flow since we perceived how



**Fig. 1.** Experiment 1. A, an example of bone rearrangement and orientation after running shallow water, with minimal bone displacement. B, another example of bone rearrangement and orientation after running deep water. Experiment 2. C, one of the examples of orientation of long bones and some compact bones parallel to the current in the river channel. D, aspect of the stream where experiment 2 was conducted.



**Fig. 2.** Experiment 3, Series One. A and B, views from opposite directions of the predominantly parallel orientation pattern produced in the transect. C, location of the experiment on the edge of the channel on the bar (red arrows indicate location of Experimental Series One; green arrows show the Experimental Series Two). D, example of bone shaft in the process of being covered by sand. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

easily they were transported away. The densest bones (namely long bone shafts) were placed in the deeper section of the channel, over a sandy side bar. Placing the bones near the flow margin allowed us to efficiently take measurements and collect them without creating turbulence or modifying the sandy sedimentary floor, which could have affected the final orientation of other specimens. Furthermore, this strategy also allowed us to place bones along a 4 m transect, reducing the risk of clustering them in a small space, which could have resulted in imbrication of bones and shadow-effect loci where bones may have adopted anomalous orientations caused by interdependence for stabilization. The transect was considered the cluster area and in the 2 m surrounding it we established a buffer area in which bone movement was considered para-autochthonous. Bone transport outside the buffer area was considered allochthonous. The velocity near the flow margin was 34 cm/s and that in the deeper part of the transect was 52 cm/s. The velocity was strong enough to move all specimens, even those occupying the shallowest portion of the flow and barely covered by

water. Experimental Series Two involved placing all bones inside the deeper part of the transect, which had a serious repercussion for certain bones, which were transported away from the transect. Series One allowed us to see the orientation patterns of all the bone specimens. Series Two enabled us to study differential bone transport in addition to orientation patterns. Three experiments of each series were performed to have a good sample and range of variation.

Bones were placed inside the channel for different lengths of time. Series One was exposed to the flow for 30 min. Series Two was exposed to the action of the flow for one hour. Both, the SLA and the DA-axes were measured and compared to the current direction to assess which axis type was a better indication of the direction of the flow.

With these experiments, we address the issue of orientation and autochthony and the related variables of water energy and time that it takes for orientation patterns to appear. By no means do these experiments reproduce the non-stationary flow dynamics

**Table 1**

Anatomical distribution of all the bones used in Experiment 3 (three series) according to element and bone section (for long bones).

	Original		Series 1 <sup>a</sup>		Series 2 <sup>a</sup>	
	Small	Large	Small	Large	Small	Large
<b>Humerus</b>						
Epiphysis	12	6	6		12	3
Shaft	18	81		21	3	24
<b>Femur</b>						
Epiphysis	12	3			12	
Shaft	45	12	9	6	12	6
<b>Tibia</b>						
Epiphysis	24	6			15	3
Shaft	69	0	12		21	
Scapula	6	6	3		6	3
Pelvis	9	12	6	9	6	6
Mandible	6	3				
Rib	12	18	3	6	3	12
Compact	30	0	30		30	
Vertebra	0	6		3		3
Total	243	153	69	45	120	60

<sup>a</sup> Bones transported from assemblage.

and their effect on object permanence and transport over prolonged periods of exposure to continuous moderate or high water energy flows.

### 1.2. How do bone shape and bone structure affect specimen transport under the effect of water?

It has been argued that bone shape (flat, tubular, polygonal) as well as bone composition (dense versus trabecular bone) influence bone transport under the effect of a water current (Behrensmeyer, 1975; Hill, 1975; Frostick and Reid, 1983). This has never been tested in fragmented experimental assemblages. For this reason, bone specimens were measured for length, breadth and thickness. In every case, the maximum value obtained for each measurement was used. Bones were defined as “flat” when thickness was less than one-third of the B-axis, “cube” when thickness was greater than one-third of the B-axis and “tube” when the specimen was from a long bone that preserved the complete shaft section. Bone composition was divided into “trabecular”, if trabecular bone structure constituted more than one-third of the composition of the bone, and “dense” if dense tissue represented >2/3 of the specimen. Given the larger sample size and the natural fluvial setting where the experiment was carried out this type of analysis was carried out only on the bone assemblage used in Experiment 3.

**Table 2**

Distribution of long bone shafts according to three size categories and carcass size in Experiment 3 (both series, including three experiments of each), showing the original number of specimens prior to experimentation and the number of specimens transported away from the transect after each experiment. Numbers in parentheses show the percentage of bone loss for each size category.

	Original		Series 1		Series 2	
	Shafts	Epiphyses	Shafts	Epiphyses	Shafts	Epiphyses
<b>Small carcasses</b>						
<30 mm	27	0	6 (22.2)	–	9 (33.3)	–
31–60 mm	81	12	9 (11.1)	6 (50)	21 (25.9)	12 (100)
61–90 mm	15	27	6 (40)	–	3 (20)	24 (88.8)
>90 mm	6	0	–	–	–	–
<b>Large carcasses</b>						
<30 mm	24	0	3 (12.5)	–	9 (37.5)	0
31–60 mm	39	0	18 (46.1)	–	21 (53.8)	0
61–90 mm	21	0	6 (28.5)	–	–	0
>90 mm	6	15	–	–	–	3 (20)

Specimen orientation was used as an indicator of orientation regarding the water current direction. Each specimen was classified as “transported” if it experienced no movement or was locally rearranged within the boundary of the experimental transect, or as “non-transported” if it was transported away from the experimental transect.

### 1.3. Archaeological analysis of the orientation pattern from recent excavations at TK

Three field seasons have been carried out by TOPPP at TK (2010–12). Excavations have been conducted in two sectors. In sector A, located adjacent to the northeast of Leakey's Trench I (North sector), 74 m<sup>2</sup> have been excavated so far, which comprised 52 m<sup>2</sup> of preserved TKLF (TK Lower Floor). Sector B is situated between Leakey's Trenches I and II and current work has unearthed ~28.5 m<sup>2</sup>, in which TKLF was preserved in 9.6 m<sup>2</sup>. The Upper Floor (TKUF) was identified in a reduced northwestern portion of Sector A and west of Sector B. A thorough geological and archaeological report is in progress. Both archaeological levels occur in a silty clay deposit, indicative of low energy conditions.

De la Torre and Benito-Calvo (2013) analyzed orientation patterns from Leakey's Trench II. According to Leakey (1971), TKUF and TKLF were excavated in Trench I, and only TKUF was excavated in Trench II (Leakey, 1971; Fig. 86, p. 186). However, the map drawn by Leakey shows a level topographically and stratigraphically situated in the position of TKLF (work in progress). In the stratigraphic profile of the only remaining wall of the outcrop, TKUF can be clearly identified on the western wall ~30–40 cm above TKLF. In that position TKUF would represent only a small portion of the western area of Trench II. As a consequence, the map drawn by Leakey (1971, Fig. 86; de la Torre and Benito-Calvo, 2013, Fig. 3) shows materials from both levels in the western part of the trench and probably only materials from TKLF in the eastern part of the trench. The hippopotamus remains from Sector I and Sector II as drawn by Leakey (1971, Fig. 80 and 86) could potentially correspond to the same individual. This has some consequences in the interpretations described in several publications, where assemblages assigned to the Upper Occupation have an important component of artefacts derived from the Lower Occupation.

In Sector A, the density of lithic artefacts in the Lower Occupation (TKLF) is 66 pieces per m<sup>2</sup> (including shatter). This density, one of the highest reported for any Olduvai site, would be even higher if surface pieces without coordinates were included. This density of lithic artefacts is considerably higher than the figure of 46.8 pieces per m<sup>2</sup> recorded by Leakey in Trench I (Leakey, 1971: 261), which probably suggests that in her excavations of the site artefacts may have been selectively collected and therefore not all may have been drawn on the maps.

A full report of the site is in progress, but here we will show the spatial analysis of lithic artefacts in a portion of the excavation, large enough to provide meaningful statistically-based interpretations. The site was photographed and mapped using laser total stations (Fig. 11). Orientations taken directly on the map will be reported here. In order to compare with de la Torre and Benito-Calvo's interpretations, we used a 1.6 elongation index and their same GIS approach by automatically obtaining MBR (minimum bounding rectangle) axes from rectangles encasing each elongated item with the aid of ArcGIS. Orientation data were obtained comparing D axis, MBR and SLA.

### 1.4. Graphic representation

Orientation of elements in these assemblages was carried out by taking orientation measurements with a compass. Then data

were processed with RockWorks 15.0 software, which allowed the use of statistical approaches to the elaboration of rose diagrams. Mean vector values were used and 95% confidence intervals were displayed to show the variation of the main trend. Petals in the rose diagram sometimes occur in colors other than blue, to show preferential orientations (trends). Isotropy is defined by  $\text{Magnitude} < \text{Mean Percentage} + \text{Standard Deviation}$ . Slightly anomalous orientation is indicated by  $\text{Mean Percentage} + \text{Standard Deviation} < \text{Magnitude} < \text{Mean Percentage} + (\text{Standard Deviation} \times 2)$ . Moderately anomalous orientations are defined by  $\text{Mean Percentage} + (\text{Standard Deviation} \times 2) < \text{Magnitude} < \text{Mean Percentage} + (\text{Standard Deviation} \times 3)$ . Strongly anomalous orientations are defined by  $\text{Direction} > \text{Mean Percentage} + (\text{Standard Deviation} \times 3)$ .

### 1.5. Statistical analysis

Data were statistically treated by using R. Data were originally obtained in degrees and were subsequently turned into radians and then coerced into circular objects through the “circular” R library. Isotropy (or randomness in orientation) can be statistically assessed by using omnibus tests. For this purpose, Kuiper’s test ( $V$ ) was used. To test uniform distributions against unimodal distributions, Rayleigh’s ( $R$ ) test was applied (Fisher, 1995). A model for assessing the normal distribution of circular data is the von Mises distribution. For this distribution, the dispersion is quantified by a concentration parameter  $k$ , with  $k = 0$  corresponding to an isotropic distribution and increasing values with a trend towards anisotropy. The Watson ( $U^2$ ) test is a goodness-of-fit statistic for the von Mises distribution and is recommended as a general test for uniformity. Values with  $p > 0.05$  indicate that the null hypothesis of isotropy cannot be rejected. The three tests were applied in the present study and the R functions used were “rayleigh.test”, “kuiper.test” and “watson.test” from the R “circular” library. Results were double-checked against the same tests from the “CircStats” R library. A third check for significance was carried out by comparing results with those provided by Oriana 4.0.

Statistical comparison between the transported and non-transported sub-assemblages was carried out to determine the influence of dimensional properties (quantitative variables) and categorical characteristics (qualitative variables: shape and bone composition) in the movement undergone by each specimen. We used a Multiple Factor Analysis (MFA) to analyze the joint effect of categorical and numeral continuous variables in the sample. Multiple Factor Analysis is frequently used in datasets where variables are structured into groups, each of them comprising sets of continuous or categorical variables, which are simultaneously analyzed. Sets of variables are close or distant if elements that show proximity in one set of variables also show proximity in a different set of variables. The analysis was done using the “FactoMineR” library of R.

SLA and D axes were compared against the current direction by using a  $V$  test (Mardia and Jupp, 2000). This test is a variant of the Rayleigh test, in which the null hypothesis of uniformity is tested against a hypothesis of anisotropy with a specified mean direction. This test was performed with Oriana 4.0. As a complement, it was also performed by the “v0.test” function of the “CircStats” R library. Both results are shown. Additional information compared was circular standard deviation, concentration ( $k$ ) and length of mean vector ( $r$ ) of both axes. Larger  $r$  values (indicative of concentration of orientation values), smaller standard deviations and higher values of the  $V$  test were used as criteria for selecting which axis better indicated the directionality of the water current. This analysis was carried out only on elongated bone specimens with clearly defined A-axes ( $>$  twice longer than B-axes) which were found to

move parallel or sub-parallel to the water current. Axis choice was indicated by the highest value of the  $V$ -test and  $k$  and the smallest standard deviation.

## 2. Results

### 2.1. How much bone movement is required until it shows a preferred orientation?

#### 2.1.1. Experiment 1

Most bone fragments were rearranged in the flume in a distance shorter than 100 cm from their original location, with an average distance of 34 cm from their original depositional place before they showed different orientations from their original ones. Only the very small fragments occasionally were transported beyond that distance. Water force was so weak that most small and larger fragments remained close to one another and no size sorting was documented (Fig. 1). On average, less than 10% of the sample was transported beyond 50 cm and although transport distances varied, they were mostly less than 125 cm. Under such minimal disturbance conditions, bones systematically changed their original orientations and in every experiment run, bones showed a statistically significant orientation pattern within the first 50 cm of their original placement locations (Table 3). In both types of experiments (shallow and deep water), the predominant orientation was parallel to the direction of the water current. In shallow water, more transverse orientations were documented than in deeper water. This supports Toot’s (1965) original observations that when bones are only partially covered by water, specimens with long axes tend to align perpendicular to the current, whereas in deep water, they predominantly adopt a parallel position. Bones larger than five cm were more likely to stay in their original positions even when their orientation was modified. Omnibus tests show that the null hypothesis of uniform distribution against a unimodal or multimodal pattern is rejected (Table 3).

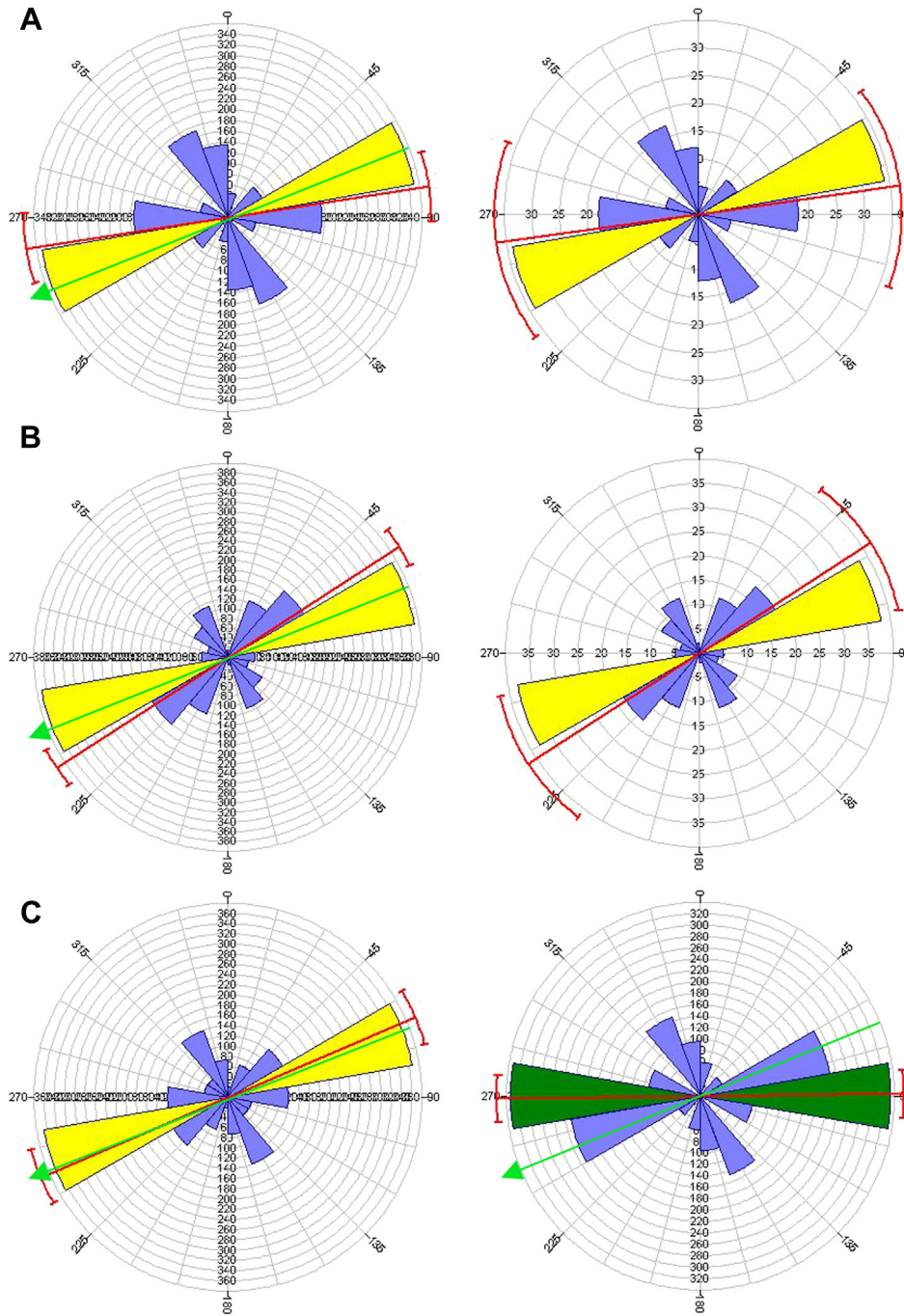
However, given that the force of the water was so low and the time of exposure so short, the resulting orientation pattern was rather trimodal instead of simply bimodal (Fig. 3). The parallel-transverse pattern was complemented with an oblique pattern

**Table 3**

Statistical tests (Rayleigh’s, Kuiper’s and Watson’s tests) for each experiment including the whole sample and the large and small carcass subsamples.  $P$  values  $< 0.05$  indicate significant anisotropy.

Carcass size	A-axis <sup>a</sup>	Rayleigh test		Kuiper test		Watson test	
		Z	p	V	p	U <sup>2</sup>	p
<b>Experiment 1</b>							
	SLA	0.5581	<0.000	5.8702	<0.01	2.4551	<0.01
	D	0.639	<0.000	6.1964	<0.01	3.1909	<0.01
<b>Experiment 2</b>							
	SLA	0.462	<0.000	3.076	<0.01	0.691	<0.01
<b>Experiment 3 (Series 1)</b>							
All	SLA	0.4711	<0.000	6.0215	<0.01	3.153	<0.01
All	D	0.413	0.006	5.0928	<0.01	2.306	<0.01
Small	SLA	0.5721	<0.000	6.0397	<0.01	3.3696	<0.01
Small	D	0.5327	0.017	5.9642	<0.01	2.9987	<0.01
Large	SLA	0.1265	0.08	3.2912	<0.01	0.6988	<0.01
Large	D	0.3472	<0.000	3.1781	<0.01	0.7854	<0.01
<b>Experiment 3 (Series 2)</b>							
All	SLA	0.5019	<0.000	5.5846	<0.01	2.6698	<0.01
All	D	0.5312	<0.000	5.8519	<0.01	2.8971	<0.01
Small	SLA	0.4419	<0.000	4.0197	<0.01	1.2844	<0.01
Small	D	0.4134	<0.000	4.0197	<0.01	1.2027	<0.01
Large	SLA	0.7438	<0.000	4.5829	<0.01	1.9274	<0.01
Large	D	0.7806	0.002	5.1778	<0.01	2.0602	<0.01

<sup>a</sup> SLA, Symmetrical longitudinal axis, D, polygon diameter.



**Fig. 3.** Rose diagrams showing the trimodal longitudinal-oblique-transverse orientation documented for bones from the shallow-water (A) and deep-water (B) experimental sets, and both combined (C, left). Red diameter and arcs indicate 95% confidence intervals of mean vector; that is, the confidence interval around the vector mean that most likely contains the true population mean direction. Green arrow shows the direction of the water current. Data were processed by bootstrapping each experimental set (1000 times) for graphs on the left column and bottom row. The bottom right rose diagram (C, right) shows orientations when using an A-axis defined by polygon diameter. Notice its difference in orientation when compared to a sample where orientation was taken using the longitudinal symmetric A-axis. Green petals indicate slightly anomalous orientation. Yellow petals show moderately anomalous orientation (see [Methods](#) for statistical explanation of these categories). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

adopted by several bones irrespective of their shape and length. Several specimens were not aligned parallel but slightly oblique to the direction of the current, usually after having undergone some rearrangement. This is better documented in the experiments using shallow water (Fig. 3a). In this case a parallel-oblique pattern is observed.

An important factor in the clustering of fragments was the “shadow effect” in which larger specimens acted as a barrier for

smaller specimens and they clustered together, frequently showing a similarly parallel orientation (Fig. 1b).

Under the minimal disturbance conditions reproduced, longitudinal axes showed a tighter orientation to the direction of the water current than did the maximum-length A-axes (Fig. 3). In this case, only those specimens where the maximum-dimension axis and the longitudinal axis coincide show the same direction as the water current.



### 2.1.2. Experiment 2

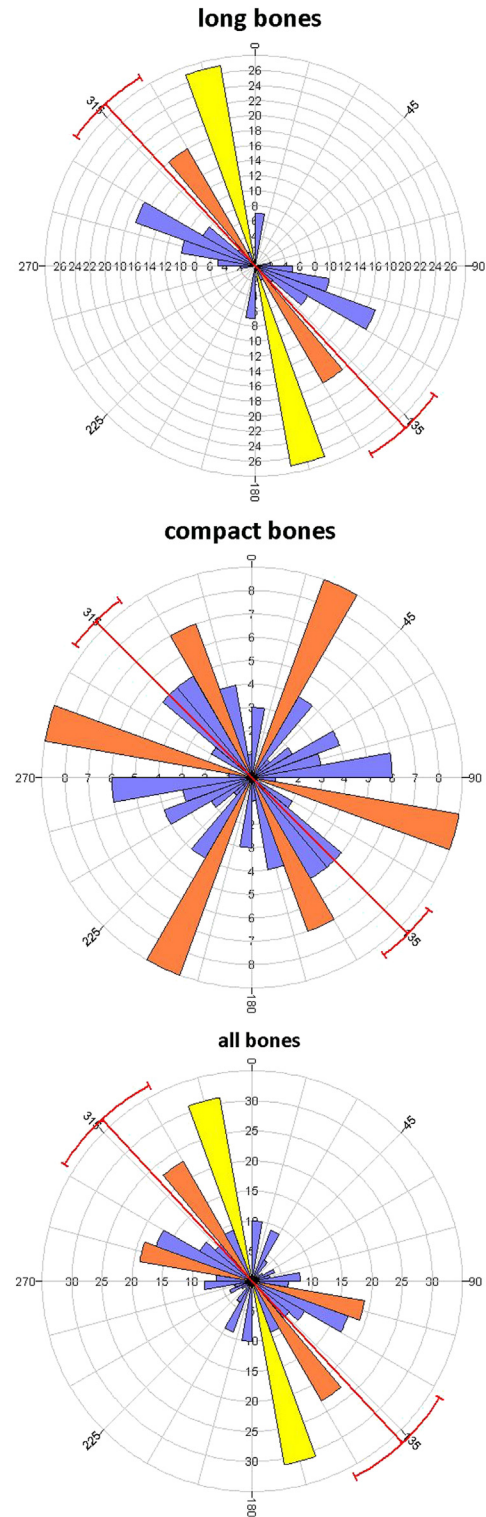
An immediate effect of the water current was the separation of long bone fragments and compact bones. The latter, pertaining to Voorhies' Groups I & II, were transported away from their initial depositional spot. The maximum distance that any long bone fragment moved prior to stabilization was 43 cm. The maximum distance that compact bones moved prior to being stabilized by the gravel was 283 cm. This experiment showed that bones can show similar orientations from just local rearrangement rather than major transport. Since the water current was stronger that used in the flume, several of the smaller shaft fragments moved away from the larger ones, including the ends. The average vector of all azimuths ( $317^\circ$ ) is very similar to the direction of the current ( $320^\circ$ ), indicating a predominant alignment parallel to the direction of the current. Long bone fragments show a higher trend toward being parallel to the current, whereas more variability is observed among compact bones due to the circumstantial nature of the gravel floor that acted as a trap and prevented further bone transport (Fig. 4). Statistical tests applied to long bones and compact bones separately, as well as the complete assemblage, show significant probability values towards anisotropy (Table 3).

### 2.1.3. Experiment 3

The first experimental series showed that most bones, regardless of element, moved a few cm from their original positions prior to adopting a predominantly parallel position to the water flow, with transverse and oblique positions being less frequent (Figs. 2 and 7). Most of the assemblage was rearranged locally, although about 28% of bones were transported away from the transect (Table 1). Bones that were transported involved 100% of compact bones, 62% of pelves, 50% of vertebrae, 30% of ribs, 25% of scapulae and 18% of limb bones with a bias towards epiphyseal ends. Pelves and scapulae tended to align parallel to the current despite their irregular shape (Fig. 2). Ribs showed an orientation of their arcs also parallel or oblique to the water flow. Mandibles showed a tendency to align their rami oblique to the water flow. Some long bones also showed the same trend, although most of them were parallel and, to a lesser extent, perpendicular to the water flow. Bones comprising ends with shaft sections tended to align parallel to the current, but the most common pattern was with the epiphysis situated in the direction of the flow.

The second experimental series showed these patterns even more accentuated (Fig. 5). When all bones were placed in the deeper part of the transect, most cancellous bones (especially those of the smaller carcass) were moved away from the transect. About 100% of the compact bones, 75% of scapulae, 57% of pelves, 50% of ribs, 50% of vertebrae and 40% of long bones were transported away from the depositional transect and the buffer zone. In the case of long bones, 81% of the epiphyses from the small carcass and 60% of the epiphyses from the larger carcass size were also transported away. Surprisingly, the bulk of the remaining bones was made up of long bone shafts irrespective of carcass size and specimen size (Tables 1 and 2). Therefore, while only 20% of epiphyses resisted one hour of water flow, 71% of long bone shafts survived in the transect without much rearranging.

When looking at shaft size (Table 2), no clear trend of specimen transport according to size is evident. It is true that smaller specimens from small carcasses were lost at a higher frequency than bigger specimens, but the opposite is documented for specimens from larger carcasses. The reason for this is that long bone shafts, regardless of size, were easily stabilized in the channel bed, to an extent in which it was frequently difficult to photograph the assemblage with all its components exposed due to the sandy bed load transport partially or completely burying



**Fig. 4.** Rose diagrams showing the orientation patterns for Experiment 2, according to long bone fragments, compact bones and the complete assemblage. Orange petals indicate slightly anomalous orientation. Yellow petals show moderately anomalous orientation (see Methods for statistical explanation of these categories). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

them. The sandy substrate ensured that when each specimen obtained a stable position against the current, that stability was not disrupted for the complete hour that the experiment lasted (Fig. 6).



**Fig. 5.** Experiment 3, Series Two. A, part of the assemblage showing the parallel–transverse orientation pattern, showing variously-sized specimens stabilized after one hour of water flow. The epiphyses are oriented against the water current. B, measuring the water current velocity with a velocimeter. C, close-up of several smaller fragments oriented with a predominant parallel direction. D, close up of orientation directions of four differently-shaped bones. Arrow indicated direction of the water current.

The autochthonous assemblages in these experiments, exposed to the water flow, reacted by adopting an anisotropic orientation (Table 3). In the first experimental series, both using the symmetrical longitudinal axis (SLA) or the polygon diameter (D) axis, parallel orientation to the flow was predominant, with the exception of the pattern of bones from large animals when using SLA. The first observation is that although the trends of the mean vector are similar in most cases regardless of axis type (Fig. 7), both axes clearly produce different results (see below). All the experiments produced statistically significant orientations against a unimodal pattern and a multimodal pattern. The most divergent results were

observed when comparing patterns in bone orientation from large carcasses (Fig. 7). Results are more similar when comparing small carcasses because most shafts were very elongated and with little variation in angles when using SLA or D axes.

The second experimental series showed an even more accentuated longitudinal orientation pattern than the first series (Fig. 8). As was the case with the previous experiment, the major discordances between both axis types occur in the large carcass bones, which were more heterogeneously shaped than the elongate bones from small carcasses. The virtual coincidence in preferred long-axis orientation of the bones and the flow



**Fig. 6.** Cluster of small-sized specimens (mostly long bone shafts) in their depositional locus showing typical parallel-perpendicular orientation to the water flow (arrow), after being exposed for one hour to a current running at 50 cm/s. Notice how some of the smallest fragments adopt an oblique orientation.

direction indicates the strong influence of the water current in the orientation of the assemblage.

The oblique orientations are caused by irregularly-shaped bones and by the smaller-sized shaft fragments which stabilize at random orientations (Fig. 6). If we divide the shaft sample into two subsamples, those specimens  $>50$  mm and  $<50$  mm, this becomes more evident (Fig. 9). Small fragments show more random orientations than longer specimens. This has extreme relevance in understanding that orientations taken from drawings of small objects will not show the real trend of the assemblage or even the direction of the rearranging force, especially if those are not properly drawn.

Both series in the Experiment 3 assemblage were sampled by randomly selecting 100, 50 and 25 specimens and testing if they reproduce the anisotropic pattern of the assemblage. This was done to test the effect of sample size on orientation patterns (Table 4). Omnibus tests show that these subsamples reproduce the anisotropy when sample size is  $>25$ . Small sample sizes ( $n < 25$ ) fail to detect the patterns of the complete sample and should not be taken as indicators of either isotropy or anisotropy.

When comparing both axes (SLA and D), a  $V$  test showed that although both axes could be confidently used to infer current direction ( $p < 0.01$ ), given that they were measured on specimens intentionally selected for their alignment to the water current, the SLA was a better indicator of the actual flow direction (Table 5). Vector length ( $r$ ) and concentration values ( $k$ ) were higher in SLA compared to D axes and, inversely, variance and standard deviation were lower in SLA both in experimental Series One and Two.

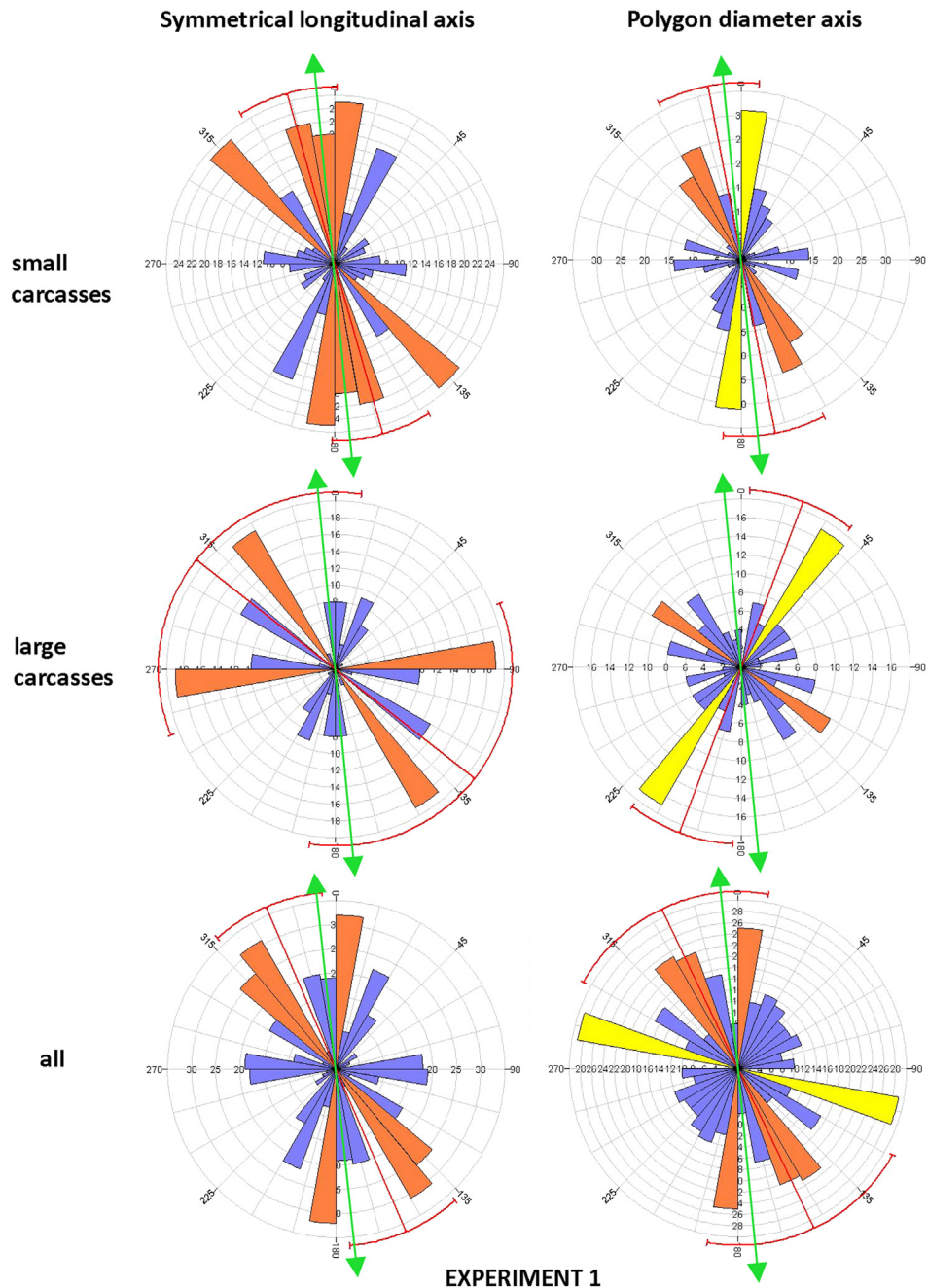
An analysis of bone shape and bone transport and orientation was also revealing. A MFA yielded a two-dimension solution explaining  $>70\%$  of the sample variance. The factor analysis of the qualitative variables produced only two variables with loadings scores  $>0.6$ : angle (0.90) for the first dimension and length (0.94) for the second dimension. Specimen breadth and thickness scored lower and were not included in the confirmatory analysis. The qualitative analysis showed (when divided into factors) that the highest weight to the solution was provided by bone structure (dense [0.75], trabecular [0.75]) and by shape (flat bones [0.70]) for the first dimension. The second dimension was influenced by bone structure (0.13) and shape, more specifically, tube shape (0.12). When considering within sample inertia, the three most prominent qualitative categories for the first dimension were tube shape (16.52), cube shape (14.56) and trabecular bone structure (10.31).

The second dimension within inertia was influenced by bone structure –trabecular (3.28) and dense (2.14)- and tube shape (1.27). This MFA separated remarkably well the experimental sample of transported and non-transported bones showing that most non-transported bones oriented parallel to the current direction are dense and flat. Trabecular bones and specimens that show a tubular or cube shape are preferentially transported away (Fig. 10).

## 2.2. Archaeological analysis of the orientation pattern from recent excavations at TK

From the previous experiments, differences in orientation patterns could be argued to be partially due to the use of different A-axis types. SLA and D axes showed similar but different patterns. In the analysis of the TK map from the recent excavation, we used a BMR axis to show that the divergences between the orientation currently documented at the site and those reported earlier are due to different mapping procedures and biases. A collection of 645 lithic items showed an elongation index  $>1.6$ . These appear in Fig. 11 as artefacts (with their shapes drawn) and small lithic objects (drawn with both poles as lines). Rayleigh's test ( $Z = 0.522$ ,  $p = 0.594$ ), Kuiper's test ( $V = 1.573$ ,  $p > 0.15$ ) and Watson's test ( $U^2 = 0.1$ ,  $p > 0.50$ ) show clear isotropy in the complete assemblage. If we use the sub-sample of the artefacts drawn with their shapes ( $n = 315$ ) (Fig. 11c), Rayleigh's test ( $Z = 0.583$ ,  $p = 0.558$ ), Kuiper's test ( $V = 1.129$ ,  $p > 0.15$ ) and Watson's test ( $U^2 = 0.055$ ,  $p > 0.50$ ) also show uniform distribution of the assemblage. These results supporting isotropy are replicated when using SLA instead of MBR axes: Rayleigh's test ( $Z = 0.227$ ,  $p = 0.797$ ), Kuiper's test ( $V = 1.115$ ,  $p > 0.15$ ) and Watson's test ( $U^2 = 0.066$ ,  $p > 0.50$ ).

The pattern documented at the level is strikingly different from that inferred if using Leakey's (1971) published map of the same site and archaeological level. In the recent excavation, no preferred orientation is documented, with the confidence intervals of the mean vector comprising virtually  $360^\circ$ . In contrast, the azimuth data reported by de la Torre and Benito-Calvo (2013), based on Leakey's map, show a strong anisotropic pattern (although they do not report confidence intervals in their data). Given that the recent excavation is a continuation of Leakey's excavation and the trenches excavated are adjacent to hers, the reported pattern suggests that Leakey's maps are strongly biased at this site and are

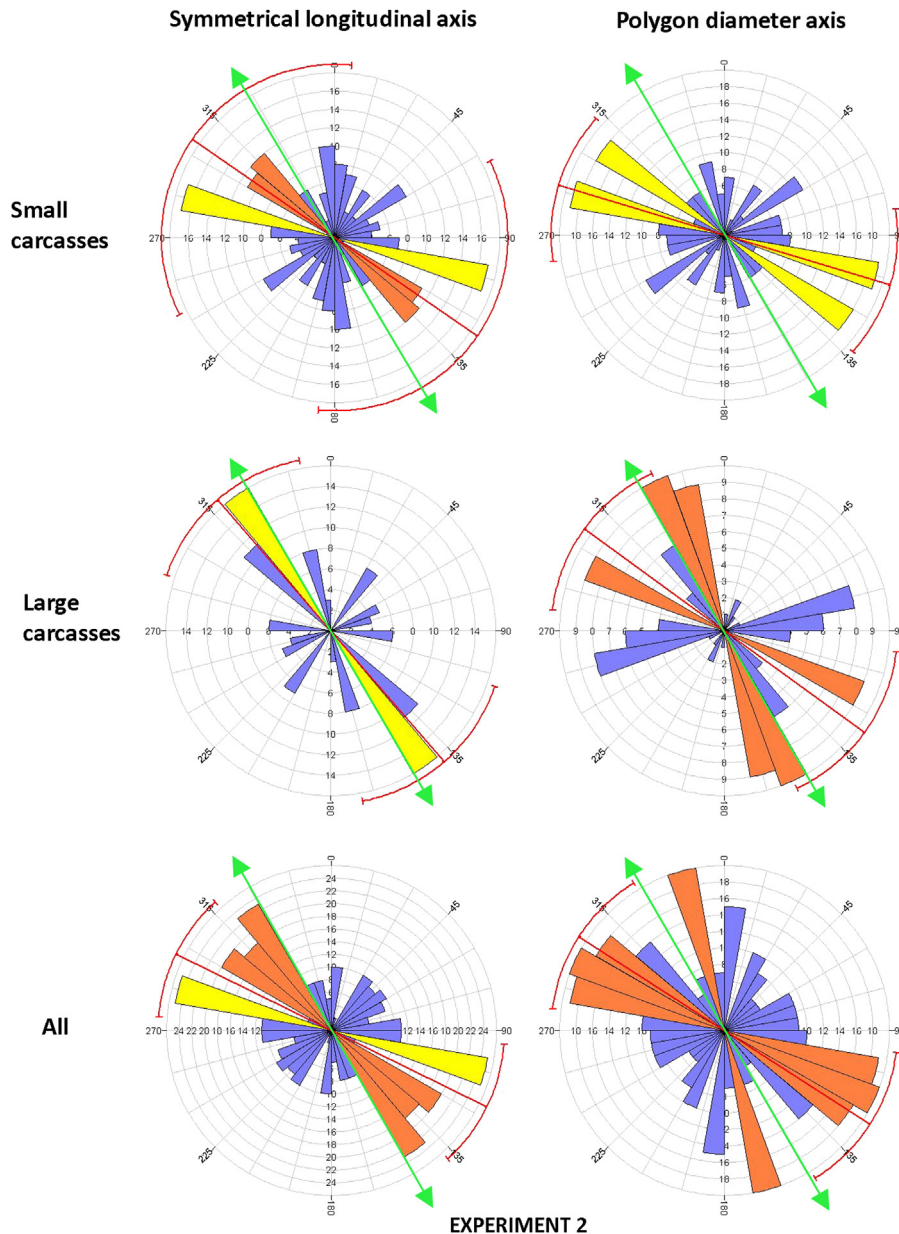


**Fig. 7.** Rose diagrams showing the longitudinal-oblique transverse orientation patterns for the Experimental Series One in the Manzanares River, divided in two columns: one using the symmetrical longitudinal axis and the other one, using the polygon diameter axis. Red diameter and arcs indicate 95% confidence intervals of mean vector; that is, the confidence interval around the vector mean that most likely contains the true population mean direction. Green arrow shows the direction of the water current. Orange petals indicate slightly anomalous orientation. Yellow petals show moderately anomalous orientation (see *Methods* for statistical explanation of these categories). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

neither comprehensive nor accurate representations of the TKLF excavation. As further proof, [Leakey \(1971\)](#) reports 15 handaxes at TKLF, whereas in her drawing only eight are evident. Out of these eight complete handaxes, and based on their dimensions ([Leakey, 1971: 175](#)) at least four handaxes should have been included in the analysis by [de la Torre and Benito-Calvo \(2013\)](#) because their elongation index is  $>1.6$ . [De la Torre and Benito-Calvo \(2013\)](#) did not, however, include them in their representation of Leakey's map either. These results cast serious doubts on the accuracy of Leakey's map drawings. Inferences based on those maps are thus scientifically unsupported.

### 3. Discussion

In the revision of the bone orientation patterns documented at several Olduvai Bed I sites, [de la Torre and Benito-Calvo \(2013\)](#) assume that such patterns “provide a general assessment of the effects of water disturbance at Olduvai Gorge”. Whereas water could be a reason for bone orientation, it certainly is not the only possibility. Experimental work has shown that other processes (wind, trampling, gravity) can generate statistically-supported orientation patterns ([Bertran et al., 1997](#); [Domínguez-Rodrigo et al., 2012](#) and references therein; [Krajcarz and Krajcarz, 2013](#)).

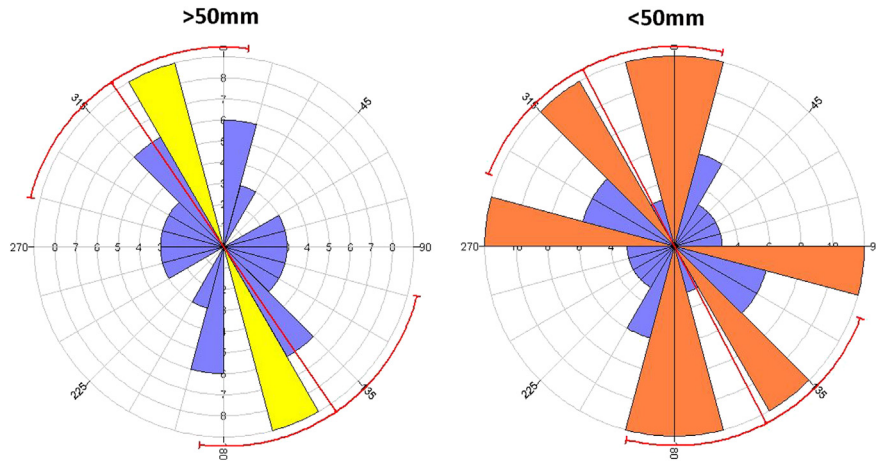


**Fig. 8.** Rose diagrams showing the longitudinal-oblique transverse orientation patterns for the Experimental Series Two in the Manzanares River, divided in two columns; one using the symmetrical longitudinal axis and the other one, using the polygon diameter axis. Red diameter and arcs indicate 95% confidence intervals of mean vector; that is, the confidence interval around the vector mean that most likely contains the true population mean direction. Green arrow shows the direction of the water current. Orange petals indicate slightly anomalous orientation. Yellow petals show moderately anomalous orientation (see [Methods](#) for statistical explanation of these categories). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The silogism “orientation = water effect = bone transport” is epistemologically unwarranted and requires further support from other taphonomic indicators to avoid equifinality. What fluvial experiments have shown so far is that transported bone assemblages will show size-sorting and anatomical selection, virtual lack of refitting, microabrasion (if transport is over a short distance) and polishing and macroabrasion if transport is over longer distances and the assemblages are allochthonous (Toots, 1965; Isaac, 1967; Voorhies, 1969; Schick, 1984). These characteristics are either marginal or undocumented in most of the Olduvai Bed I assemblages purportedly showing anisotropic bone orientations.

De la Torre and Benito-Calvo (2013) argue that GIS methods are successful in retrieving orientation data from excavation plans. This is true, but an important concession is made by using this

methodology: it is assumed that plans accurately represent the excavated assemblages. We showed previously that this is not the case for some Olduvai sites, where the objects drawn by Leakey (1971) represent just a fraction of those retrieved, where several pieces that appear in photographs were not drawn, others were drawn in the wrong place, or if in the right place, they showed incorrect orientations (Figs. 12 and 13; see also Domínguez-Rodrigo et al., 2012; Fig. 4); most of them also showed incorrect dimensions and frequently even incorrect shape (Figs. 13 and 14). This latter factor is crucial for providing orientation information, especially (and not exclusively) when “polygon diameter” (i.e., axis providing the largest metric dimension) is used (see below). De la Torre and Benito-Calvo (2013) have overlooked these arguments, insisting that these orientations do exist. We argued that these orientation



**Fig. 9.** Orientation patterns for long bone shafts according to size. Orange petals indicate slightly anomalous orientation. Yellow petals show moderately anomalous orientation (see Methods for statistical explanation of these categories). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

patterns were not secure and were very probably inaccurate, as recent excavations at FLK North show (Domínguez-Rodrigo et al., 2012). The inferred patterns were so inaccurate that they could not be used to make inferences on the purported archaeological orientation patterns and their relation to wind direction or other physical properties of the lake basin at a regional scale. In the face of evidence stemming from the comparison of the photograph and drawing of FLK Zinj, the arguments *in contra* provided by de la Torre and Benito-Calvo (2013) are easily falsified (Table 6).

The discussion of the Zinj photograph is not a trivial one. It is one of the few testimonies that we have to examine the assertion that Leakey's maps are accurate representations of the archaeological sites that she excavated. If one measures the orientation of the longitudinal axes of most of the objects (identifiable as fossils or bones) that show an elongation index >1.5 in the Zinj photograph (Fig. 12), the result shows a slight trend in a similar direction as shown by de la Torre and Benito-Calvo (2013; Fig. 8), although these authors did not find any significant anisotropy when using the D or MBR axes on this photograph. Neither did we in the present study when using SLA: a Rayleigh test ( $Z = 0.23$ ,  $p = 0.796$ ), a Kuiper test ( $1.024$ ,  $p > 0.15$ ) and a Watson test ( $U^2 = 0.048$ ,  $p > 0.50$ ) yielded negative results. Even if we combine both Zinj Fig. 8a and b in de la Torre and Benito-Calvo's (2013) work, using their BRM axis, which is the closest of their axes to our SLA, anisotropy is still unsupported: the Rayleigh test ( $Z = 2.686$ ,  $p = 0.068$ ), Kuiper test ( $1.464$ ,  $p > 0.15$ ) and Watson test ( $U^2 = 0.152$ ,  $p > 0.15$ ) indicate that the null hypothesis of isotropy cannot be rejected. The positive significance values reported by these authors for their Fig. 8b are highly dependent on a very small sample size ( $n = 17$ ), which does not reliably reproduce the assemblage's isotropic or anisotropic fabric (see Table 4). Fig. 12 shows how the rose diagram provides a large confidence interval of the mean vector direction, which

**Table 4**  
Random sampling of Experiment 3, comprising the complete bone assemblage, to test what sample sizes reproduce the complete sample orientation.

Number of draws		Rayleigh test		Kuiper test		Watson test	
		Z	p	V	p	U <sup>2</sup>	p
100	Series one	1.62	0.198	2.07	<0.01	0.172	0.1
	Series two	9.957	<0.000	2.703	<0.01	0.558	<0.005
50	Series one	2.776	0.062	1.888	<0.0025	0.188	<0.005
	Series two	5.601	0.004	2.041	<0.01	0.319	<0.005
25	Series one	0.078	0.927	0.856	>0.15	0.021	>0.50
	Series two	2.882	0.055	1.607	>0.15	0.179	0.1

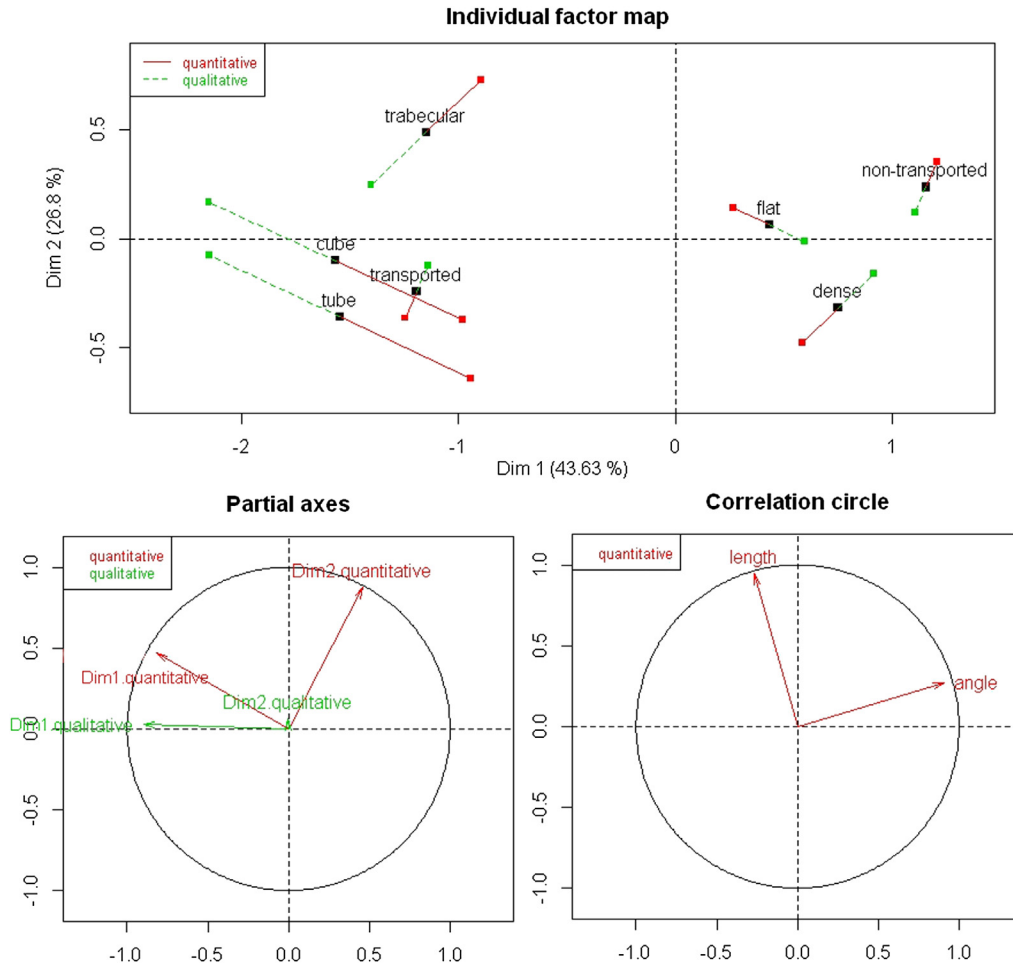
makes the trend statistically unreliable. If there were any anisotropic fabric at FLK Zinj, the number of specimens measured from the photograph (Fig. 12) would be a sample large enough to detect it, as shown for Experiment 3.

In contrast, if we use all the items in Leakey's (1971) map (Fig. 12d), a diagram with an azimuth trend showing the same direction preference appears (conditioned by the weight of the smaller and less elongated items), with a substantially shorter confidence interval (Fig. 12e). Statistically, there is significant anisotropy: a Rayleigh test ( $Z = 0.5852$ ,  $p = 0.000$ ), a Kuiper test ( $3.0702$ ,  $p < 0.01$ ) and a Watson test ( $U^2 = 0.6484$ ,  $p > 0.01$ ) are coincident in this. How can the photograph and the drawing differ so much statistically? It is because they represent two different realities.

Why does the drawing produce a more defined orientation than the photograph? If scaling each item taking the same object as a reference in both images (*Parmularius* skull), using as a scale one dimension that is different in both images (long horn) and another one that is virtually identical (short horn), we can compare shape and proportions between the objects in the photograph and the drawing (Fig. 13 and 14). When this is done, it can be seen that most objects in the drawing are more than double the size of what they should be. More importantly, most objects in the photograph are well elongated (with index >2.0), whereas almost half of the objects in the drawing are much less elongated, with an elongation

**Table 5**  
V-test (performed with Oriana 4.0 and R) and other circular data for SLA and D axes in specimens from Experiment 3.

	Oriana		R CircStats	
	SLA	D	SLA	D
<b>Series one</b>				
Length of mean vector (r)	0.784	0.642	–	–
Concentration	2.683	1.691	–	–
Circular variance	0.108	0.179	–	–
Circular standard deviation	19.972°	26.992°	–	–
V test (u)	7.535	6.082	0.9376007	0.8905781
V test (p)	<0.01	<0.01	8.40E-21	5.10E-19
<b>Series two</b>				
Length of mean vector (r)	0.757	0.627	–	–
Concentration	2.421	1.626	–	–
Circular variance	0.122	0.186	–	–
Circular standard deviation	21.38°	27.663°	–	–
V test (V)	–0.756	–0.627	–	–
V test (u)	–7.332	–6.082	0.6150831	0.5889731
V test (p)	<0.01	<0.01	4.23E-10	1.70E-09



**Fig. 10.** Multiple Factor Analysis showing the Individual Factor Map, the partial and correlation axes of both the quantitative and qualitative variables (see text for definition of each) and the distribution of factors according to each of the two dimensions. Data in the Individual Factor Map show the transported sub-assembly (negative values of the first dimension) and non-transported subassembly (positive values of the first dimension) perfectly discriminated and their relation to bone shape and structure.

index  $\sim <1.5$ . This also shows that axes from the drawing are less clear and subjective than those from the photograph. These moderately elongated objects have a major influence on how axes are determined. We selected a longitudinal axis according to the elongation direction and we assume that the software used by de la Torre and Benito-Calvo (2013) proceeded similarly, but experimental work shows that these items do not adopt the same orientation pattern as clearly elongated (index  $>2.0$ ) bones (see Experiment 3).

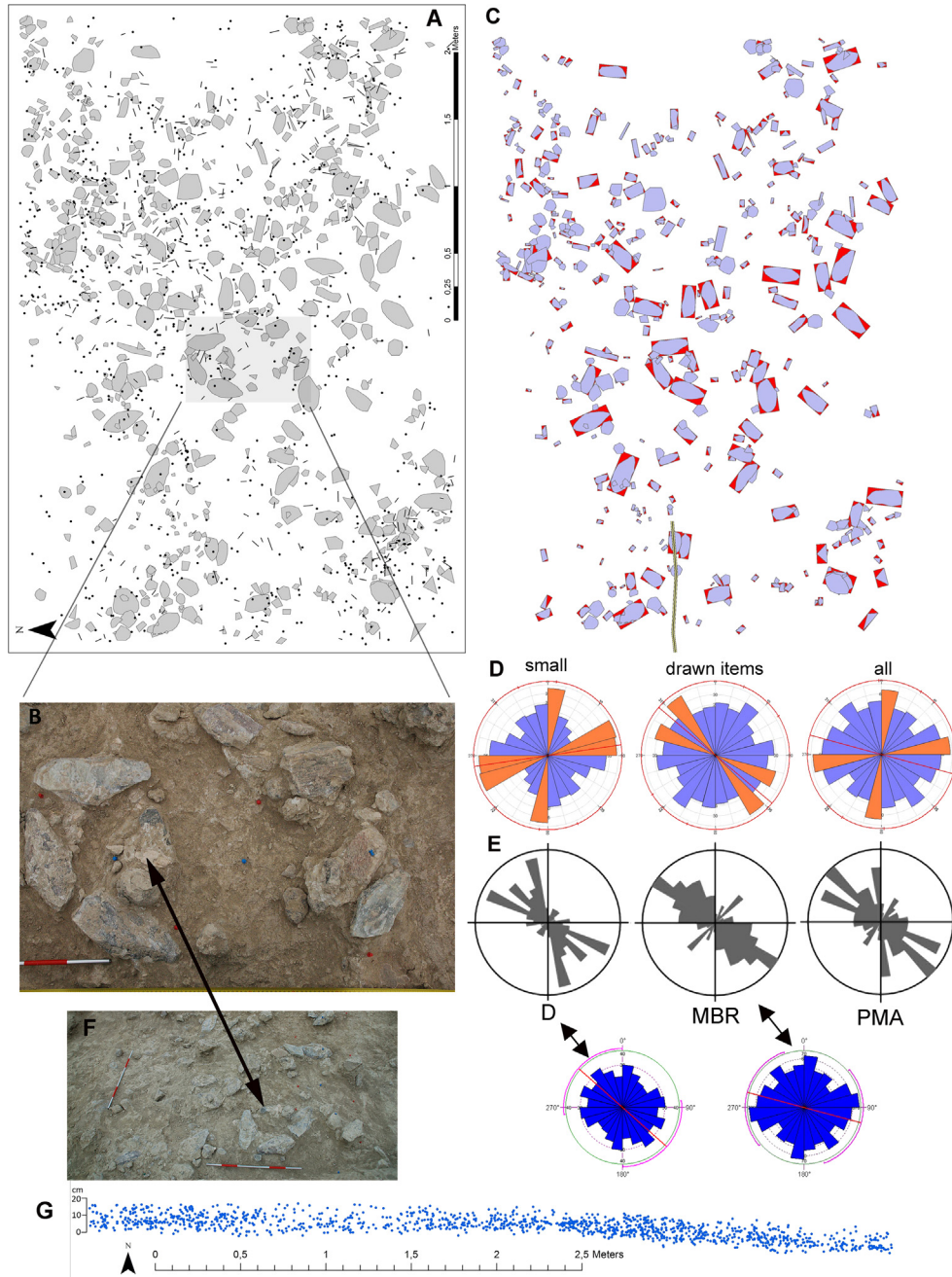
De la Torre and Benito-Calvo's (2013) new attempt to justify the orientation patterns previously documented by them from Leakey's maps is also problematic. They inaccurately attribute to Domínguez-Rodrigo et al. (2012) the interpretation that orientation should be made considering the anatomical longitudinal symmetrical axis of bones. We never made such a taphonomically-incorrect generalization and argued instead that *long* objects (i.e., long bones and long bone fragments) tend to orient according to their longitudinal axes (Toots, 1965; Voorhies, 1969; Domínguez-Rodrigo et al., 2012: 2118).

The use of inferences that are experimentally unsupported produces some inconsistencies in the interpretation of bone shape and orientation by de la Torre and Benito-Calvo (2013). Their assertion, that the "longitudinal symmetrical axis may be useful in well-preserved straight cylindrical-like bones, but it is unsuitable when bones are unevenly broken (longitudinally and/or transversally)" is contradicted by the data presented here and by other recent

experiments (Domínguez-Rodrigo and García-Pérez, 2013). Taphonomists are aware that most of the shaft fragments produced during hammerstone breakage are longitudinal (e.g., Pickering and Egeland, 2006; Pickering et al., 2006). Experiments using mainly long fragmented bones clearly show that most of the shaft fragments produced by hammerstone bone-breakage align their longitudinal axis parallel and transverse to the current, the same way as do tubular bones (Figs. 7 and 8); when adopting oblique alignments, they follow the same orientation irrespective of their shape (Figs. 1 and 6). Hammerstone breakage produces bone specimens that are individually different morphologically but their condition as elongated objects makes them react similarly under the same force.

Counter to this evidence, de la Torre and Benito-Calvo (2013) argue that "The polygon diameter index (D) is therefore an optimal tool to retrieve item orientation in assemblages with large heterogeneity of shapes". The experiments reported here show that SLA shows a more accurate alignment with the current flow than D (compare Figs. 3, 7 and 8). It could be argued that this is probably because long bone shafts are the bulk of most human-accumulated faunal assemblages. However, recent experimentation with a wide array of differently-shapes specimens shows that SLA is systematically more efficient in measuring the direction of the current than alternative A-axes such as D and MBR regardless of bone shape (Domínguez-Rodrigo and García-Pérez, 2013).

Another important methodological problem is the belief that the combined use of the minimum bounding rectangle (MBR) (i.e.,



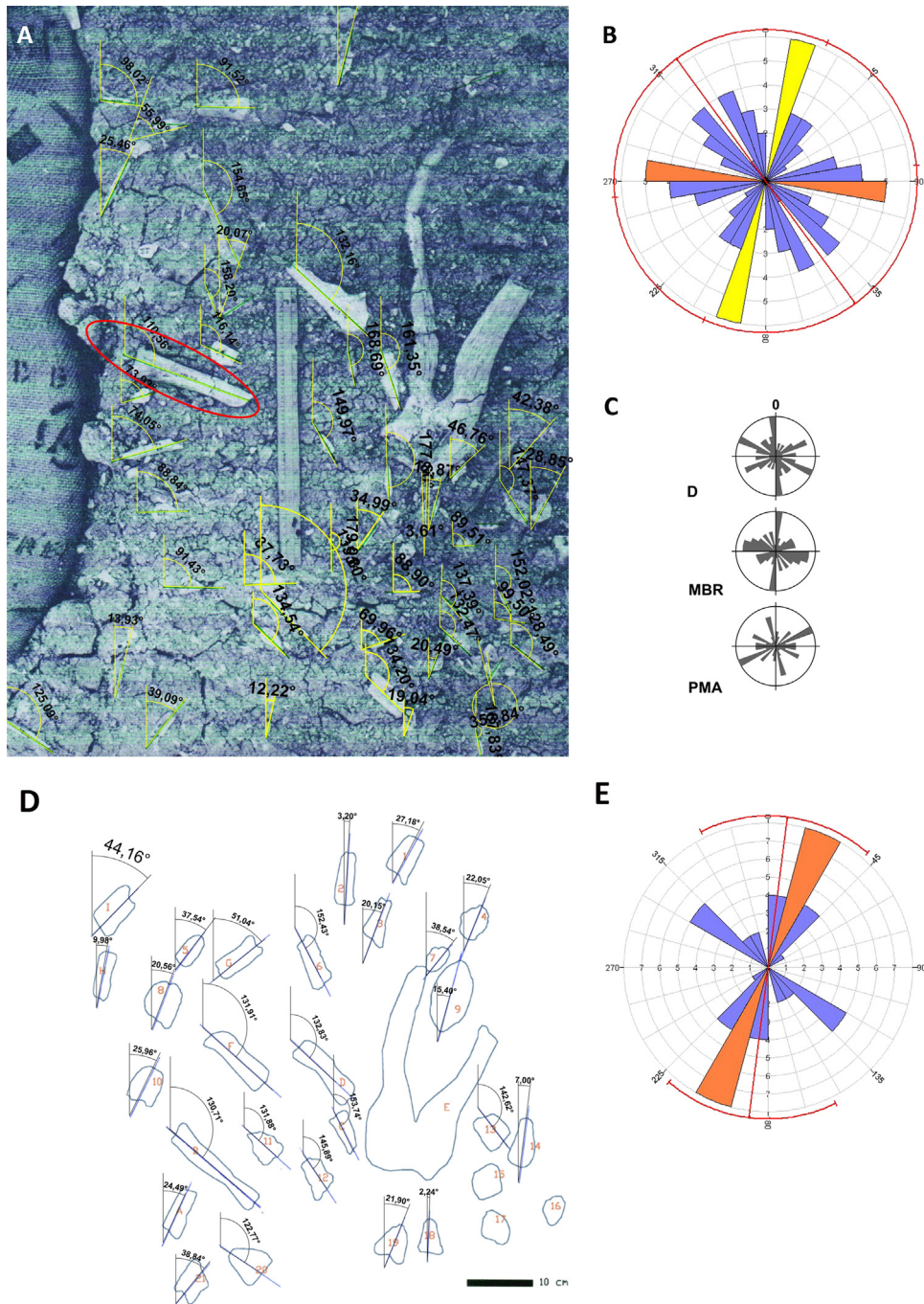
**Fig. 11.** A, portion of the equivalent of the Lower Floor of TK (Leakey, 1971) recently excavated by TOPPP. Very small lithic objects with elongation index >2.0 are drawn as polar vectors. The rest of lithic artefacts are drawn as polygons following their contour with a total station. B, a close-up of part of the floor drawn shown to compare the drawing with the photograph. C, selection by ArcGIS of drawn artefacts with an elongation index >1.6 and encasing with rectangles to derive their A-axis. D, rose diagrams of the small polar lithic objects, the drawn artefacts and the complete lithic assemblage with elongation index >1.6 using the MBR axis. Orange petals indicate slightly and statistically non-significant orientation. E, rose diagrams of lithic artefacts from de la Torre and Benito-Calvo (2013) from the drawing of the same level as drawn by Leakey (1971), showing orientation patterns derived from the D, MBR and PMA axes. Notice the striking differences between Leakey's drawing and the recent one obtained using total stations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

boxing each specimen) and the polygon main angle (PMA) reinforces interpretations derived from the polygon diameter (D). As a matter of fact there are important differences in results when using these methods (see Fig. 7 and 8 from de la Torre and Benito-Calvo, 2013). Even if MBR is closer to the longitudinal axis than D, it still does not provide an accurate description of the longitudinal axis (Fig. 15), and most importantly, it ultimately depends on whether the drawing indeed represents the original orientation of the specimen. None of these methods will produce a reliable

orientation pattern if the original drawing is an inaccurate representation of the original assemblage (Fig. 14).

De la Torre and Benito-Calvo (2013) question the validity of the compass bearings at FLK North in Domínguez-Rodrigo et al. (2012), because they are at odds with their interpretation of Leakey's maps. An obvious error in the rotation of Trench 1 during the composition of the image in Domínguez-Rodrigo et al. (2010b; Fig. 1) when compared to the distribution and orientation of the specimens in Bunn et al. (2010; Fig. 1), is mischaracterized by de la

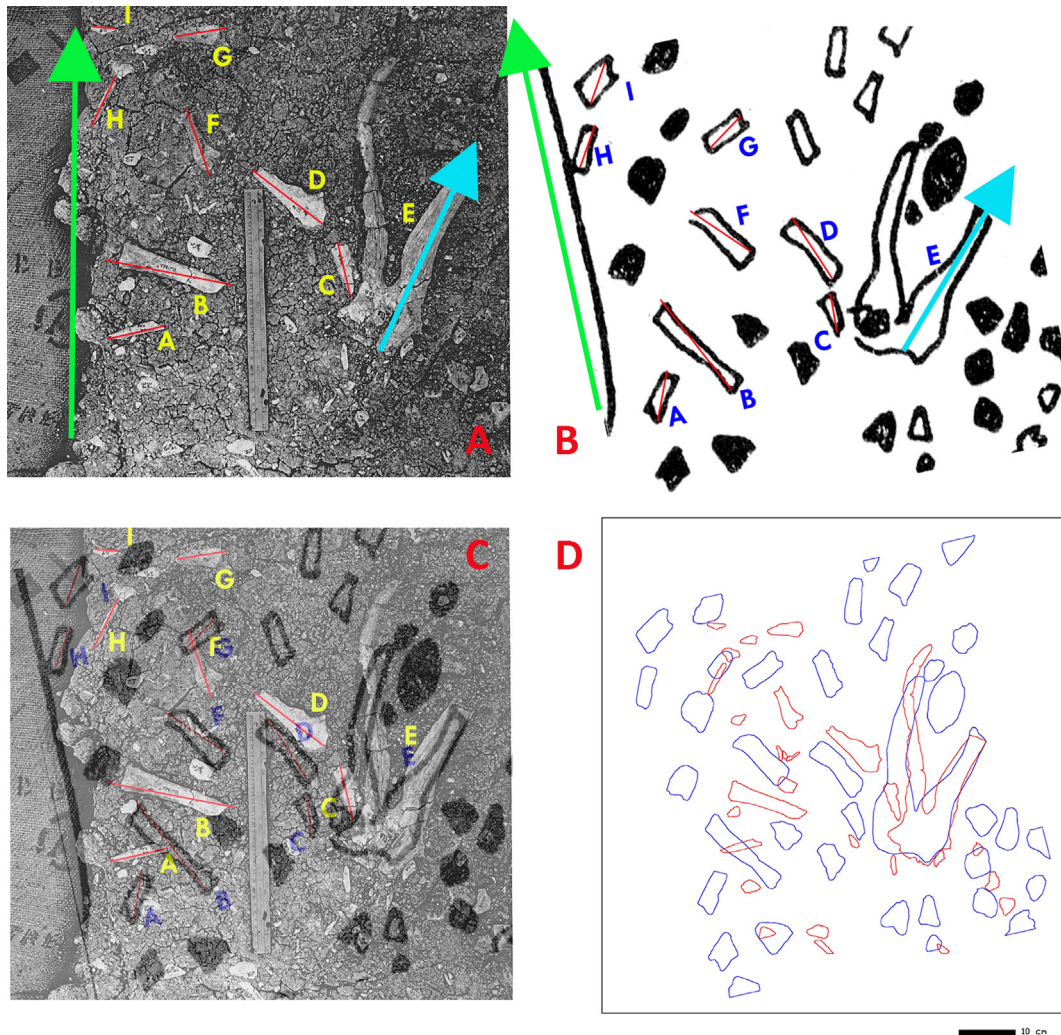




**Fig. 12.** A, Original photograph of a portion of the FLK Zinj 22 excavation (Leakey, 1971), showing selected objects ( $n = 47$ ) with their longitudinal axes. B, Rose diagram showing the orientation pattern of the objects. C, Orientation patterns documented on the same photograph by de la Torre and Benito-Calvo (2013), according to polygon diameter (D), minimum bounding rectangle (MBR) and polygon minimum angle (PMA). Statistical tests failed to find a significant value of the trends (see text). D, The drawing of the same portion of the excavation (oriented and scaled to match the photograph) showing the symmetrical longitudinal axes and measurements. E, Rose diagram resulting from plotting the azimuths of the objects in the drawing. Notice the shorter confidence interval of the mean vector when compared to the rose diagram (B) produced from the photograph raw data. It should be emphasized that the pattern documented in the drawing rests heavily on the orientation of items that do not exist or cannot be recognized in the photograph and, therefore, lack proper reference.

Torre and Benito-Calvo as “field recording problem”, even when the orientation of artefacts and fossils are the same in both figures because it is a  $180^\circ$  rotation error. The vectorized interpretation of de la Torre and Benito-Calvo (2013) of those figures finds statistically-supported orientation when the same statistical tests applied to compass bearings detects none (Domínguez-Rodrigo et al., 2012). Although de la Torre and Benito-Calvo (2013) do not specify if they took the orientation of most vectorized objects, it seems to us that they did not discriminate shape accurately,

because their measured sample comprises 610 specimens, which is 30% more than the sample that we used based on clear elongated axes (see below). De la Torre and Benito-Calvo previously used items with elongation indices  $>1.6$  (in contrast with our use of  $>2.0$ ) for their analysis of the Bed II sites, but this short index is taphonomically not well defined in terms of elongation. It has been suggested that orientation data should be derived from very elongated skeletal elements, defined as those whose A-axis is at least twice as long as the B-axis (Eberth et al., 2007). This is the



**Fig. 13.** A, Photograph of a portion of the FLK Zinj 22 excavation (Leakey, 1971), showing the reference axis (green arrow) taken as orientation for items in Domínguez-Rodrigo et al. (2012; Fig. 4) and its distortion when compared to the axis of the short horn of the Parmularius skull (blue arrow), here drawn to scale and oriented as in the photograph (B). C, Overlap of both images showing the mismatch between photograph and drawing. D, comparison of both images (photo and drawing) scaled to the same dimension as the shorter horn of the Parmularius skull and showing the mismatch between item location, orientation and size. De la Torre and Benito-Calvo (2013) mention that it is unlikely that important errors were made during artifact plotting in Leakey's drawings. Such optimistic overstatement is unsupported and disproved by this figure. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

elongation index used by Domínguez-Rodrigo et al. (2012). The use of a smaller elongation index, as used by de la Torre and Benito-Calvo (2013), produced unwarranted orientation patterns. This is probably the reason why the pattern they document on our assemblage is different from those that we reported, because we were careful not to include items without a well-defined longitudinal axis in our orientation sample.<sup>1</sup>

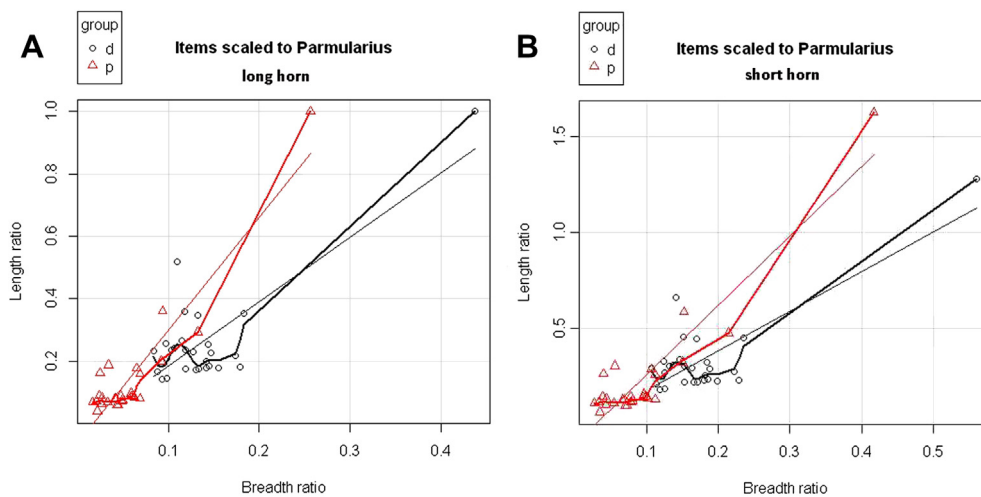
Despite this methodological difference, we reproduced our colleagues' approach of taking orientations directly from the drawings. We used GIS software (ArcGIS) to measure one by one the azimuth of longitudinal axes of elongated items in both trenches ( $n = 424$ ). Measurements were taken following de la Torre and Benito-Calvo's method; that is, "according to a relative coordinate

system in which strikes were analyzed with regards to the Y-axis of the maps, with 0° at the top". The resulting rose diagram is similar to theirs but average directions vary: the mean vector is 47° (in contrast with 68°–84° documented by de la Torre and Benito-Calvo, 2013), which shows that none of their three axis methods reproduces the SLA axis as described in Domínguez-Rodrigo et al. (2012). The slightly smaller sample we used should not make an important difference in the statistical evaluation of isotropy. We acknowledge that there is a northeast–southwest trend in our data as they appear in the drawing when excluding smaller items with irregular shapes (Fig. 16), but which were elongated enough to collect their orientation with a compass. The drawing of Trench 1 provided statistical support of isotropy (*contra* de la Torre and Benito-Calvo (2013)): Rayleigh test ( $Z = 1.796$ ,  $p = 0.166$ ), Kuiper test (1.529,  $p > 0.15$ ) and Watson test ( $U^2 = 0.135$ ,  $p > 0.10$ ). The drawing of Trench 2 provided similar results in two of the tests. A Rayleigh test ( $Z = 1.629$ ,  $p = 0.196$ ) and a Watson test ( $U^2 = 0.16$ ,  $p > 0.10$ ) supported a uniform distribution of objects, whereas a Kuiper test ( $V = 1.932$ ,  $p = 0.025$ ) suggested some multimodal distribution, against a Kuiper test of the compass data ( $V = 1.535$ ,

<sup>1</sup> In our study, "Measurements were taken for each item with a longitudinal A-axis whose length was a minimum of twice the width of the specimen (i.e. of the B-axis). This allowed the collection of orientation data from specimens regardless of their size. Thus, measurements were taken on any specimen >20 mm showing a well-defined longitudinal axis" (Domínguez-Rodrigo et al., 2012: 2118).

**Table 6**  
Objections raised by de la Torre and Benito-Calvo (2013) to Domínguez-Rodrigo et al.'s (2012) interpretation of the mismatch between the FLK Zinj photograph (Leakey, 1971) and its drawing.

De la Torre and Benito-Calvo (2013)	Reply
Domínguez-Rodrigo et al. (2012) only used a portion of the Zinj photograph	Adding a few more of those items that have a clear axis would be statistically irrelevant (see Fig. 12), especially because they cannot be confidently identified in both the photograph and the drawing. Using them without identifying them properly in both images would be comparing apples and oranges. Furthermore, our previous use of bootstrapping techniques compensated for the small sample size. The portion of the photograph used by Domínguez-Rodrigo et al. (2012) was intended not to show the presence or accuracy of the orientation, but the misrepresentation of the orientation of most artefacts and fossils in the drawing when compared to the photograph. The error in the mean vector orientation was almost of 80°, a figure that de la Torre and Benito-Calvo (2013) considered as “complete negligence” and very “unlikely” to have been made by Leakey (1971).
Domínguez-Rodrigo et al. (2012) never stated the criterion used to assign A-axes.	This is a mischaracterization, since in the figure caption we specified that the A-axes used were as described by Benito-Calvo and de la Torre (2011); that is, D (polygon diameter).
Unwarranted correspondence between items on the plate and the drawing	This assertion is unjustified since the small sample of objects used was selected precisely because of the reliability in identifying the same objects in the drawing and the photograph. It is obvious that more items other than the <i>Parmularius</i> skull can be confidently identified in both images (e.g., A,B,C,D,F,G in Domínguez-Rodrigo et al. (2012), Fig. 4). The hesitation by de la Torre and Benito-Calvo (2013) is another proof of the mismatch between item location and orientation in the photograph and drawing.
The main problem for our colleagues is that Domínguez-Rodrigo et al. (2012) compare a map that has a clear northing reference (Leakey, 1971: Fig. 24), with a photograph (Leakey, 1971: plate 8) that has no geographic orientation.	This would be a problem if we intended to match the direction of the orientation patterns in both images, but that is not the case. We intended to show the divergent orientation models represented in both images (predominantly unimodal; symmetric bimodal in the photograph and predominantly bimodal; symmetric quadrimodal in the drawing), with different modes of mean vectors, because the drawing is <b>not</b> an accurate representation of the photograph. See Fig. 13c, where when using the <i>Parmularius</i> skull scaled to a similar size in the photograph and similarly oriented in the drawing, there is no correspondence in location of items and the orientation of several bones are strikingly different when comparing both images. In addition there are several items in the photograph that were not drawn and items in the drawing that do not exist in the photograph. Unsurprisingly, most items in the drawing seem substantially disproportionate absolutely (compared to the photograph) and relatively (when scaled to the size of the <i>Parmularius</i> skull). This is clear proof that “substantial mistakes” were made when mapping objects at FLK Zinj.



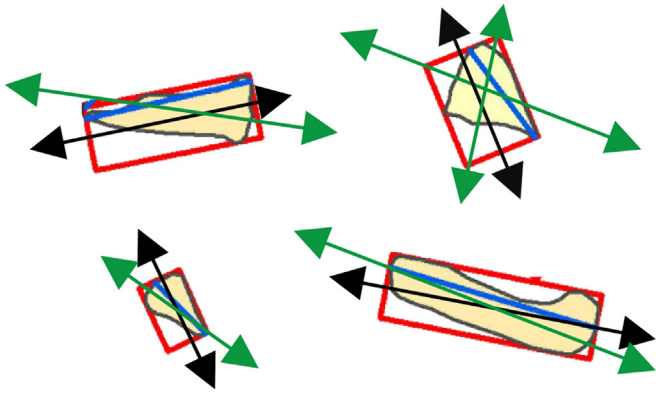
**Fig. 14.** Plots of the breadth and length ratios obtained of dividing absolute dimensions of each item by the length of the big horn (A) and short horn (B) of the *Parmularius* skull, taken as a reference (Fig. 12). The dimensions of the short horn in the photograph and scaled drawing are very similar. The graph shows the regression line plus the trajectory of the shape trend. Key: p, Leakey's (1971) Zinj photograph; d, Leakey's (1971) Zinj drawing. Legend: d, drawing; p, photograph.

$p > 0.15$ ). In order to overcome the differences of these tests, a distance approach to uniform distribution was carried out by using Rao's Spacing test, which showed that isotropy could not be disproved ( $U = 140.109$ ,  $p = 0.10$ ).

The separation of both trenches when discussing their orientation patterns is necessary because they represent different portions of the vertical deposit of FLK N 1-2. The FLK North site, comprising one of the thickest archaeological deposits known for the African early Pleistocene, spanning more than six meters of strata, represents hundreds or thousands of years of formation (Leakey, 1971). It is difficult to conceive of the persistence of a water flow in the same direction over such a vast time span, without a direct trace of its prolonged existence either in the form of fluvial sedimentation or channel structure, contrary to what Benito-Calvo and de la Torre

(2011) maintain. In substantially shorter depths (~70 cm), deposits formed under the influence of a fluvial system (e.g., WK, Bed IV) showed that orientation trends varied according to the depth of the deposit (Hill, 1975).<sup>2</sup> Fig. 17 shows that at FLK N 1-2 there is a slight difference in the orientation patterns seen in Trench 1 vs. Trench 2. The drawings in Trench 1 and 2 represent two different

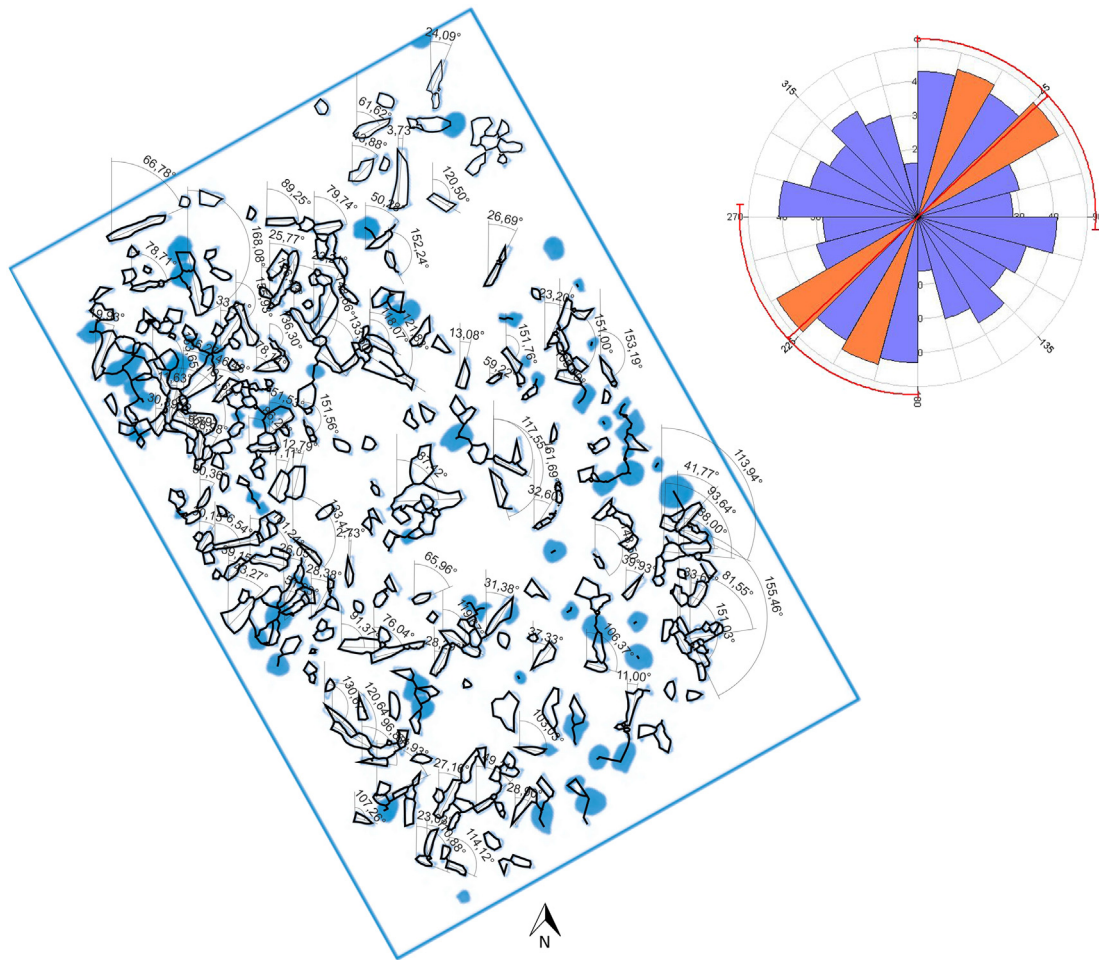
<sup>2</sup> We previously claimed that our work “was the first time in the history of field research in the Bed I sites that item orientation was documented directly” with compass (Domínguez-Rodrigo et al., 2012: 2117). Despite criticism (de la Torre and Benito-Calvo, 2013), this statement still holds. Previous orientation data with compass was carried out by Hill (1975) at “Old DK”, a 2 m<sup>2</sup> trench that he excavated away (>300 m) from the DK site (Leakey, 1971). No correlation with DK was provided.



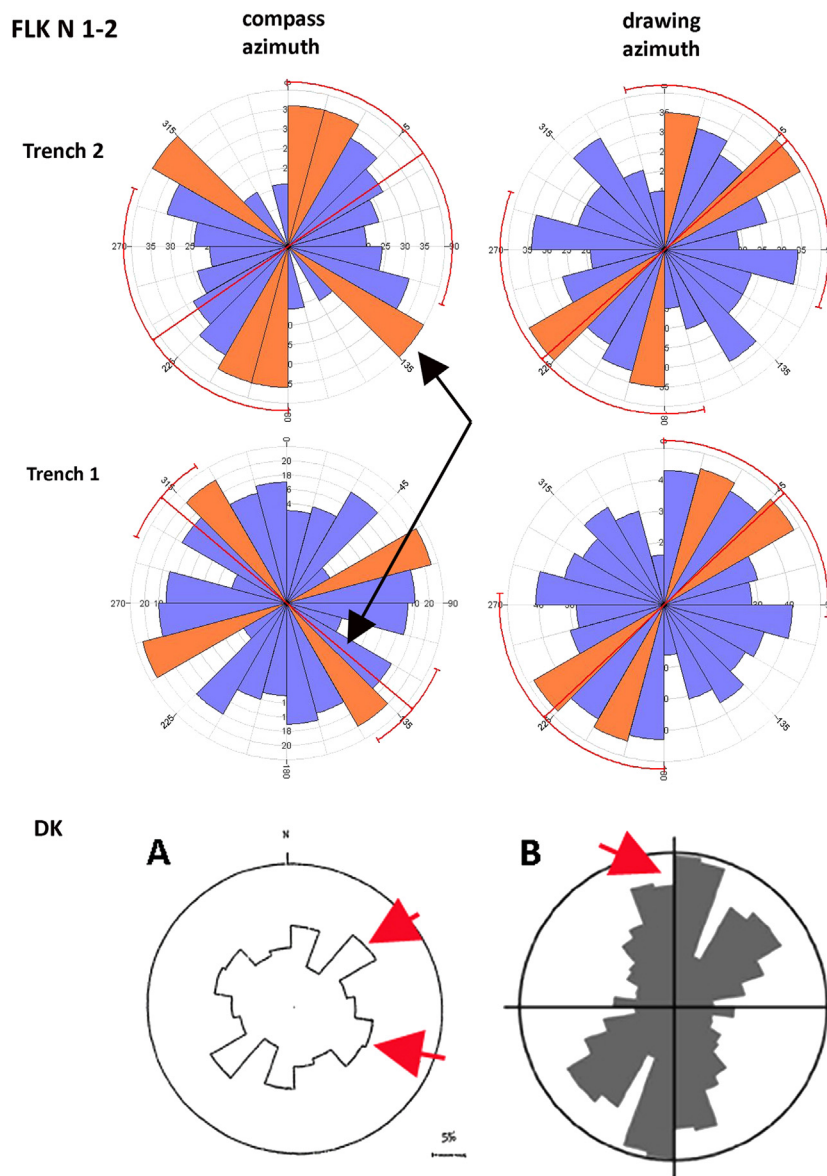
**Fig. 15.** Some examples from de la Torre and Benito-Calvo (2013) showing the axis measured by the MBR method (black arrows) and the longitudinal axis documented in taphonomic experiments (SLA) (green arrows). Notice the divergent angles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

portions of the actual distribution of specimens at FLK N 1-2. Leakey (1971) defined this level as having a varying depth of 2–3 feet, although most of the objects were located in its upper portion. Domínguez-Rodrigo et al. (2010a,b) showed a combined drawing of

our identification of the FLK N 1-2 level and three separate drawings representing each of the three 10 cm spits in which we identified the level. Trench 2 comprises only the upper section (~ 10 cm) of Level 1-2, which was identified as Level 1 (Bunn et al., 2010). Given that this trench provided a slightly anisotropic orientation against the multimodal pattern provided by Kuiper's test and that Trench 1 showed a statistically-supported isotropic fabric of its materials, one reason that would explain the difference in the patterns between both trenches is that one of them represents a sequence that is substantially deeper than the other and includes materials from a larger array of depositional events. When only the first 10 cm spit of FLK N 1-2 in Trench 1 is analyzed, separately from the remainder of the deposit, anisotropy results are statistically supported, even to a stronger degree than in Trench 2, by Rayleigh's test (0.6977,  $p < 0.000$ ), Kuiper's test ( $V = 3.8843$ ,  $p < 0.01$ ), and Watson's test ( $U^2 = 1.2104$ ,  $p < 0.01$ ). This shows that the depositional processes from the upper part of the sequence may have differed from those of deeper parts of the deposit, because once we analyze the complete deposit anisotropy disappears. We do not know if Leakey's map of FLK N 1-2 represents the uppermost portion of the site, where the density of materials is high, or the complete vertical sequence of the 1-2 level, but differentiating between both options is crucial in order to avoid comparing apples to oranges, especially when comparing Bunn et al.'s (2010) drawings with Leakey's (1971) as done by de la Torre and Benito-Calvo (2013).



**Fig. 16.** Example of how orientations were taken on longitudinal axes on elongated objects from the drawing of Trench 1 at FLK North 1-2 and rose diagram showing the results of the orientations from items measured in Trench 1 and Trench 2 (Bunn et al., 2010). Trench 1 is oriented according to North. Orange petals show slightly anomalous orientations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



**Fig. 17.** Orientation trends in FLK North (Trench 1 and Trench 2), comparing azimuths from compass and drawings (Bunn et al., 2010). Notice how the NW–SE trend (arrows) is not significantly detected on the drawings. Orientation trends in DK comparing azimuth information (A) (Hill, 1975) and Leakey’s (1975) drawings (Benito-Calvo and de la Torre, 2011). Arrows show trends that are different or not reproduced in both contexts. Orange petals show slightly anomalous orientations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

A very relevant outcome of the reconstruction of orientation patterns using azimuth data derived directly from the map drawings is that it underscores the slightly different patterns obtained when using a compass. Fig. 17 shows the orientation patterns identified in FLK North when using both methods. Despite fine control in map drawing, data derived from a compass produce an orientation pattern that is not faithfully reproduced through drawing. The abundance of very small fragments retrieved from the site that are frequently not properly shaped in the drawing show less clear axes than when taking orientation measurements with a compass and for this reason are excluded when selecting objects from the drawing to plot. This is shown in both trenches, where an important NW–SE trend is unappreciated in the drawing. Current research by TOPPP is focusing on producing drawings with the total station data and with photogrammetry, which eliminate these types of errors. These important differences in orientation trends are also documented at other Bed I sites. For instance, at DK, the

azimuth data produced a different orientation pattern (Hill, 1975) from that reported by Benito-Calvo and de la Torre (2011) from Leakey’s drawing (Fig. 17) in the same area.

Methodologically, it has been argued that it is “unrealistic to plan on mapping all elements presented at a site when fossils are widely distributed in three dimensions” (Eberth et al., 2007: 271). This is probably why Leakey’s maps are incomplete recordings of the sites since in most of them the number of objects represented is much less than the number of fossils catalogued. Trend and plunge measurements for a complete assemblage can be more accurately recorded by using a compass and clinometer.

It has been argued that the presence of water, specifically a river as suggested by Blumenschine et al. (2012), would explain the orientation of FLK Zinj, FLKNN and FLK N (de la Torre and Benito-Calvo, 2013). This remains unsupported by the conflicting data between orientation patterns drawn from the FLK Zinj photographs, modern excavations at FLK N, and inferences drawn from

Leakey's drawings, and also because no direct physical evidence exists to justify the presence of a river in the immediate vicinity of FLK Zinj (work in progress) (*contra* Blumenschine et al., 2012). Evidence contradicting the link made by de la Torre and Benito-Calvo (2013; Figs. 6 and 7) between anisotropy and secondary position comes from the orientation pattern documented by them at FLK North 6. The bulk of the bones accumulated in this level belong to a fairly complete carcass of an elephant. The size of the animal and its semi-articulated state show that the elephant died at the site in the absence of any water transport. However, the resulting orientation pattern shows the same trend as in all of the overlying levels. The amount of fluvial force required to move proboscidean bones would have produced a high-energy setting capable of bringing clasts into the site and eroding the flat clay layer upon which the elephant was found, forming erosional features such as channels or flute marks. No such evidence is found.

The Olduvai sites meet the basic definition of a “bonebed”: dense concentrations of bones from various animals, which are stratigraphically discrete and whose density contrasts with bone density in the surrounding landscape (Rogers and Kidwell, 2007). Most bonebeds have been interpreted as autochthonous or para-autochthonous, i.e., locally deposited (Rogers and Kidwell, 2007). Experiments in fluvial contexts over several years have shown that fluvial systems tend to disperse not concentrate bones (Aslan and Behrensmeyer, 1996). In a 9-year period of exposure of 311 experimental bones and observation of >300 natural bones for 13 years, it was documented that most bones had moved less than 1000 m from their point of origin (Aslan and Behrensmeyer, 1996). This shows that bones tend to stabilize early and are not prone to form accumulations due to water flows. In the light of available evidence, Rogers and Kidwell (2007: 24) “find it conceptually difficult to accept the proposition that disarticulated bones and teeth of numerous animals delivered from widely separated point sources at different times would travel downstream through complex and hydraulically unstable channel belts and collectively accumulate on a regular basis”. Rogers and Kidwell (2007: 25) argue instead that “bones and teeth would tend to disperse instead of concentrate as a function of differential transport. It is more likely that many, if not most multi-individual concentrations of disarticulated vertebrate skeletal elements preserved in ancient fluvial channels were derived from a preexisting concentrated source”. This (para) autochthony can also be inferred from taphonomic analyses for various of the Olduvai bonebeds (e.g., Domínguez-Rodrigo et al., 2007).

#### 4. Conclusions

A topic that is ambiguous in de la Torre and Benito-Calvo's (2013) work is their insistence in conceptually linking orientation patterns to primary position of sites. They do not define what they understand by “primary position”. If this means recovery in the same state as remains were left upon abandonment, we are skeptical that this exists in the Pleistocene record. For instance, carnivores gorging on abandoned bones will redeposit them. If what they mean is that items are retrieved in the same area where they were initially deposited, that is autochthony, as we explained earlier (Domínguez-Rodrigo et al., 2012). If this is what they mean by primary position, then the conceptual link between orientation and secondary position is epistemically unwarranted. The present work shows how significant orientations can be detected in autochthonous assemblages. Orientation patterns, thus, are insufficient to determine if any given assemblage is autochthonous or allochthonous, but fortunately, a wealth of other taphonomic variables can be used to discriminate between these possibilities.

Experiments in natural fluvial settings have shown that even under a moderately strong current of 50 cm/s, bone assemblages have the potential to stay within the boundaries of their depositional locus. The fragmented nature of the assemblage may be advantageous for quick stabilization of fragments, since it was discovered that even if Voorhies' transport groups reflect the nature of the modification of the assemblage when exposed to water flows, some fragments belonging to Group I (such as ribs) may have higher chances of remaining in the depositional spot in contrast with other elements from Group I & II (such as phalanges). Overall, bones with a trabecular structure and grease deposits act similarly regardless of Voorhies group. For the same carcass size, fragmented epiphyses (Group II) may be as easily transported as ribs and compact bones (Group I and I & II). Although a trend for smaller fragments to be transported away was detected within the same bone type, overall, size was not as influential in bone transport as bone structure. Most epiphyses and ribs are >50 mm in length and they were transported more easily than shaft fragments <50 mm. These results show that to properly evaluate the impact of water in the deposition of any given assemblage, size distribution is not relevant without considering bone structure and element type. These results also caution against using information derived from artificial experimental settings. Although work in flumes can provide better control of the variables used, the artificial setting may impact the outcome of the experiment. For instance, Pante and Blumenschine (2010) argue that there is an inverse relationship between animal size and transportability of long bone fragments, with smaller animals being represented in allochthonous assemblages, whereas lag assemblages are biased toward the larger animal components. These authors also claim that shaft fragments are transported more easily than epiphyseal fragments. Both interpretations are unsupported in our recent experiments, where “lag assemblages” retain a large portion of the small fauna component and epiphyseal ends are more readily transported than shafts. The contrast in interpretations may be the result of Pante and Blumenschine (2010) having used a flume and most of our experiments having been carried out in a natural fluvial setting, in which the sedimentary substrate is crucial for stabilization.

In all of the experimental series presented here, assemblages showed a statistically-supported orientation of bones locally, without having undergone any major bone transport and with bone fragments remaining within the depositional transect and its buffer area in variable proportions (>70%–55%), depending on the current velocity and location with respect to the river margin. The experiments have also shown that both for elongated items and for complete assemblages, the symmetrical longitudinal axis provides a better indication of the water flow direction. Whether that is contingent upon the selection of bones and their shapes needs further experimentation before making this a generalization, although preliminary studies targeting the influence of bone shape in orientation patterns suggest that the symmetrical longitudinal axis is the most accurate A-axis type (Domínguez-Rodrigo and García-Pérez, 2013). Supporting this, it is notable that non-longitudinally-shaped bones from the present experiment, such as scapulae, tended to orient parallel to the current direction.

How does this affect interpretations of bone orientation patterns reported for Olduvai sites? These results show that the assumption that Leakey's plans accurately reflect orientation patterns of each bone assemblage is unsupported. This can only be scientifically addressed on a site by site basis, by exposing a new area of each site and comparing object orientation with that obtained from Leakey's plans. This approach has produced negative results for FLK North, despite the similarity in the main trend observed at the modern excavations of the site when looking at

drawings (Bunn et al., 2010; Domínguez-Rodrigo et al., 2010b) and at Leakey's (1971) maps. The present work has also shown the mismatch in the drawing of the FLK Zinj and the photograph where the same objects are represented. Despite interpretations of a statistically-supported anisotropic fabric of the assemblage (de la Torre and Benito-Calvo, 2013), the analysis of all the items that can be clearly identified as fossils in the photograph (not root casts, which are abundant on the paleosol) display a statistically-supported isotropy. A more thorough confirmation of the mismatch between Leakey's drawings and the excavated materials has been detailed in the present work when comparing the ongoing excavation at TK and Leakey's map of the same site.

This debate can lose itself in minor, though not unimportant, details, but the important conclusion here is that autochthonous assemblages can show anisotropic fabric of their components without experiencing any significant transport. Therefore, the questions that we can address now are:

1. Are there anisotropic assemblages at the Olduvai sites? The answer is affirmative, as ongoing recent work will show (in preparation). This can be documented in low-energy settings, and the opposite (isotropy) can be documented in higher-

energy contexts, as also observed by de la Torre and Benito-Calvo (2013).

2. Can this anisotropy be documented from site drawings? There is a high degree of uncertainty about inferring orientation patterns from drawings for reasons discussed in the present work. Hand-made drawings are not as accurate in capturing the original orientation of items as compass azimuths. Furthermore, the distortion of small objects while drawing (or their smoothing with computers) can also modify the original shape and the axis of the object. These axes are important in the configuration of orientation patterns, as shown in the present work (Figs. 6 and 9).

3. What can orientation patterns indicate about site formation? Not much *per se*, unless accompanied by an array of taphonomic variables. Orientation can be caused by multiple processes (water, gravity, trampling) (Kerbis-Peterhans, 1990; Domínguez-Rodrigo et al., 2012; Krajcarz and Krajcarz, 2013). Even stochastic processes operating in bone discard and deposition can produce anisotropy in the absence of physical forces (Domínguez-Rodrigo and Martí, 1996). The present work has shown that in a set of simulated assemblages, a little energy is enough for water to rearrange bones and produce anisotropic

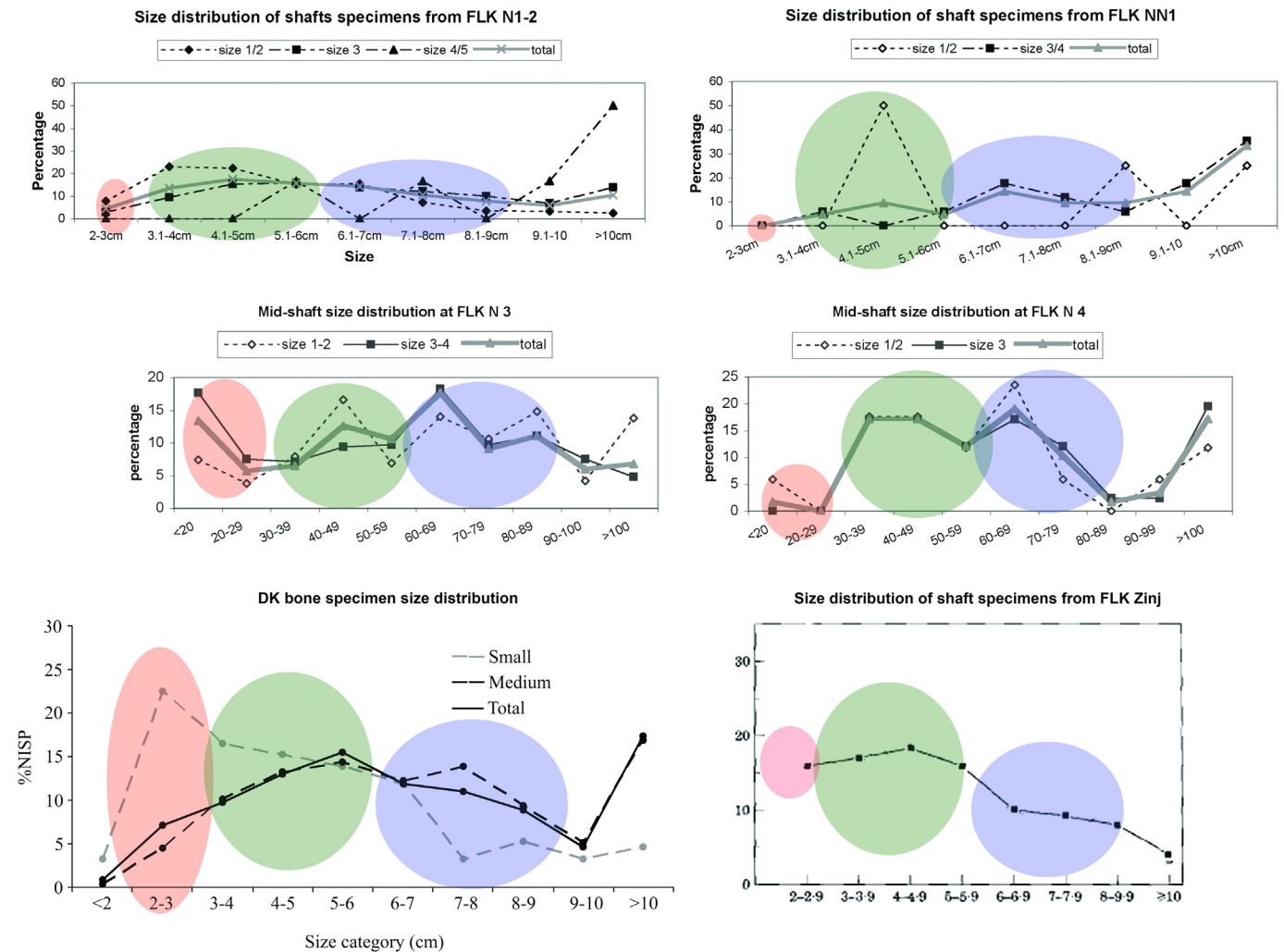


Fig. 18. Selection of published information on specimen size distribution (DK) and long bone shaft size distribution (FLKN 1-2, FLKN 3, FLK N 4, FLK NN1, FLK Zinj) from the Olduvai Bed I sites. Data were taken from Egeland (2007) for DK, Domínguez-Rodrigo and Barba (2007) for FLK N 1-2, Domínguez-Rodrigo et al. (2007) for FLK N 3-4, Barba and Domínguez-Rodrigo (2007) for FLK NN1, and Blumenschine (1995) for FLK Zinj. Each size category range appears highlighted in different color. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

fabrics. Orientation, therefore, should **not** be directly assumed to be the result of bone transport.

- How can we tell if anisotropic assemblages are the result of bone transport or local rearrangement? Bone transport implies size selection in the transported assemblage and its re-deposition. This is especially noticeable with long bone shafts. A water flow will only accumulate shaft fragments through allochthonous processes if they are included in the sedimentary matrix that it transports and deposits. This will cause size selection and physical modification of these bones. A good example can be archaeologically documented at PEEN1 in Peninj (Tanzania) (Domínguez-Rodrigo et al., 2009). In contrast, when an assemblage contains unworn shaft fragments from different carcass sizes representing the small (<30 mm), intermediate (31–60 mm) and large (>60 mm) specimen size categories, this is an indication of autochthony, since this has so far been experimentally documented only in autochthonous assemblages. The frequency of the smallest fraction of the shaft subset does not need to be ample if the site has a non-anthropogenic origin, since carnivores do not generate proportionally as many small splinters as human hammerstone bone breaking (Domínguez-Rodrigo et al., 2012). A look at long bone shaft specimen size from DK, FLK NN, FLK Zinj and FLK N shows that the distribution and accumulation of specimens from the three size categories indicates, together with the absence of evidence for bone polish and abrasion associated with bone transport, that these assemblages have an autochthonous origin (Fig. 18). This is especially relevant at FLK Zinj, where previous specimen size distribution analysis led to the interpretation of the site as a typical post-depositionally unmodified human-made bone assemblage (Blumenshine, 1995). Furthermore, even if applying Pante and Blumenshine's (2010) interpretation that mixed assemblages, containing bones from small and large animals, represent autochthonous assemblages, all Bed I sites would still be interpreted as autochthonous given the accumulation of bones from various carcass sizes in each of them. A third factor to consider is the association of compact bones with long bone fragments, which experimentally only occur in assemblages that have not undergone any significant modification by water. These elements are documented in several of these sites.

This experimental work contributes to the wealth of taphonomic information suggesting that most of the Olduvai Bed I sites are autochthonous assemblages with various degrees of local rearrangements due to the combined action of carnivores and sedimentary processes. Any behavioral model or site formation interpretation that ignores this body of evidence will be based on unsupported foundations.

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