Analysis of orientation patterns in Olduvai Bed I assemblages using GIS techniques: Implications for site formation processes

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Mary Leakey's excavations at Olduvai Beds I and II provided an unparalleled wealth of data on the archaeology of the early Pleistocene. We have been able to obtain axial orientations of the Bed I bone and stone tools by applying GIS methods to the site plans contained in the Olduvai Volume 3 monograph (Leakey, 1971). Our analysis indicates that the Bed I assemblages show preferred orientations, probably caused by natural agents such as water disturbance. These results, based on new GIS techniques applied to paleoanthropological studies, have important implications for the understanding of the formative agents of Olduvai sites and the behavioral meaning of the bone and lithic accumulations in Bed I.

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Introduction

Archaeological assemblages excavated by Mary Leakey (1971) at Bed I of Olduvai Gorge (Tanzania) are dated to between >1.84 (Tuff IB, Blumenschine et al., 2003) and 1.74 Ma (Manega, 1993; Blumenschine et al., 2003), and are probably the most renowned sites for the entire African Plio-Pleistocene. The archaeological sequence revealed by Leakey formed the foundation for highly influential interpretations of early human behavior (e.g., Isaac, 1978) and also their subsequent critique (e.g., Binford, 1981; Blumenschine, 1986; Potts, 1988). A significant part of the discussion on the behavioral interpretation of Bed I assemblages was due to disagreements about how site formation processes operated at Olduvai. Leakey (1971) proposed that most sites were undisturbed assemblages, either representing living floors (DK Level 3, FLKNN 1 and FLKNN 3, FLK Zinj) or butchering sites (FLK North 6). Although introducing some modifications, Isaac (1978) and Isaac and Crader (1981) broadly agreed with Leakey's interpretation, differentiating between vertically concentrated in situ floors and vertically diffuse disturbed assemblages.

These early views were challenged by Binford (1981), who argued that the associations between lithics and fossils resulted from depositional dynamics of stable land surfaces where non-integrated episodes led to the formation of multi-event palimpsests. Whereas Binford (1981) challenged the "vertical dimension" of the alleged Olduvai living floors, Blumenschine and Masao (1991) criticized their horizontal delimitation, proposing that the densities of fossils and artifacts were similar across the Olduvai landscape, and that therefore the concept of delimited and concentrated patches of bones and lithics accumulated by hominins (i.e., living floors) was spurious (Blumenschine and Masao, 1991). Potts (1988) reached different conclusions. He recognized that the depositional history of some of the sites (e.g., FLK North 6, DK) could have been much more complicated than what was considered by Leakey or Isaac, but Potts (1988) still believed that most Bed I sites—apart from FLKNN 2—yielded clear evidence of human interaction with animal carcasses and that the assemblages were largely undisturbed by post-depositional processes.

de la Torre and Mora (2005a) argued that complex sedimentation processes in Bed I assemblages could have led to the admixture of unmodified rocks and archaeological materials belonging to different depositional events. Based on inconsistencies in the lithic assemblages, de la Torre (2005) also cast doubts on the contextual links between the fossils and stone tools in FLK North 6–3, and the integrity of DK. More recently, this has been supported by new zooarchaeological revisions (Domínguez-Rodrigo et al., 2007), which propose that only FLK Zinj shows systematic manipulation of bones by hominins. At present, there seems to be a consensus that there were many agents contributing to the formation of the Olduvai Bed I assemblages, including hominins, carnivores and probably also other biotic agents. In recent years, most of the discussion has revolved around the role of carnivores and hominins in the formation of Bed I assemblages (e.g., Bunn and Kroll, 1986; Binford, 1988; Blumenschine, 1995; Capaldo, 1997; Domínguez-Rodrigo et al., 2007), but not so...
Background on the impact of water flow in Olduvai Bed I sites

Despite the relative wealth of studies on fluvial disturbance (Isaac, 1967; Voorhies, 1969; Behrensmeyer, 1975, 1982, 1988; Schick, 1984; Bagdley, 1986; Aslan and Behrensmeyer, 1996; Coard, 1999; and others), the application of models derived from experimental data and actualistic research to Olduvai has been rather limited as of yet. This is probably due to the existence of a consensus (arguably unfounded) over the primary position of all Bed I assemblages. Given the fine-grained contexts in which assemblages are located and the largely fresh condition of artifacts and bones, it is widely agreed that sites experienced no major post-depositional disturbance.

However, only Potts (1988) and Petraglia and Potts (1994) discussed the effects of water flow in Bed I. Potts (1988) proposed six indicators that might reveal the effects of fluvial disturbance on the Olduvai sites (sedimentology, paleogeography, artifact size classes, preferred orientations, edge abrasion and bone hydraulic transport groups), but none has provided conclusive results as yet.

With reference to the sedimentology of the sites, the clay and silt contexts of the Bed I sites (Leakey, 1971) do not automatically mean that the material therein is undisturbed. Schick (1984) points out that archaeological assemblages in clay deposits may have undergone significant disturbance, as fluvial systems may have high-energy competence even if the available sediment to transport is fine grained. With regards to the paleogeography of the Olduvai Bed I sites, Hay (1976) located most of the assemblages in low energy deposits corresponding to the lacustrine floodplain (Hay, 1976), but it has been suggested that some channels existed near DK (Potts, 1988), the FLK broader area (Blumenschine et al., in press), and even across the FLK Zinj excavation surface (Leakey, 1971).

Regarding size classes and edge abrasion of artifacts, both Petraglia and Potts (1994) and de la Torre and Mora (2005b) presented some results, but a systematic and unified assessment of size sorting and rounding of Leakey's stone assemblages is still lacking. A similar picture emerges from the fossil collections. The outstanding number of small bone fragments in sites such as FLK Zinj, where there are about 50,000 bone splinters less than 2 cm (Bunn, 1982), has been considered as the definitive proof of the absence of water sorting over the assemblage. However, several of the other Bed I assemblages such as FLKN levels 3–5, FLKNN levels 2–3 and DK, show fewer small bone fragments than expected (Dominguez- Rodrigo et al., 2007). Bone abrasion indices are also inconclusive. Potts (1988) documents the percentages of abraded fossils consistently above 10%, but the results are contradictory. As he notes, DK, the most water disturbed site on sedimentological grounds, also shows the lowest index of abraded fossils (Potts, 1988).

The application of rounding indices is equivocal in the Olduvai assemblages. In reference to lithics, de la Torre (2005) indicated that it is sometimes difficult to distinguish between water rounding and in situ weathering for Olduvai lavas, and the hardness of Olduvai quartzite would require heavy transport for the edges to present significant damage. Potts (1988) showed that abrasion indices for the fossils from Leakey's assemblages were inconclusive. Furthermore, it has also been argued that in clays and silts, precisely the deposits containing Bed I sites, fresh bone edges remain unmodified even after undergoing long distance transport (Fernández-Jalvo and Andrews, 2003).

Bone hydraulic groups and preferred orientations are other proxies proposed by Potts (1988) to determine water disturbance. Although Potts (1988) presented some preliminary results using Voorhies' groups, subsequently no one has applied this methodology systematically to the Olduvai Bed I faunas. Regarding orientation, Potts (1988) commented on the preferred directions of fossils in DK, FLK Zinj and FLKNN 3, but his comments were based on general observations and not on a systematic study of the azimuth of artifacts and bones. Statistics of artifact orientation (i.e., azimuth and inclination) have long been used to assess water flow (e.g., Toots, 1965; Isaac, 1967; Nagle, 1967; Schleiger, 1968; Voorhies, 1969; Schick, 1984; etc.) and is considered today as a powerful proxy to address post-depositional disturbance in archaeological contexts (e.g., Lenoble and Bertran, 2004; Benito-Calvo et al., 2009). However, it has never been systematically investigated at Olduvai because measurement of artifact azimuth and inclination was not common practice in the early 1960's when the major excavations at Bed I took place (Leakey, 1971).

Given the fact that several of the proxies used for the identification of hydraulic disturbance are inconclusive (see above) and that most authors agree on the important significance of artifact orientations to assess post-depositional processes, we have developed a new method to measure and analyze the strike of artifacts in the assemblages excavated by Mary Leakey at Olduvai Bed I. The results of our analysis contribute fresh data to the understanding of the Olduvai assemblages and shed new light on the effect of post-depositional processes at these sites.

Materials and methods

The Olduvai Volume 3 monograph is widely acknowledged for the quality of Leakey's field data recording methods and her accurate excavation plans (e.g., Potts, 1988), which as presented enabled spatial analysis studies (Davis, 1975; Ohel, 1977; Kroll, 1994). Bone and stone tool refit maps (Kroll, 1994) suggest primary access to the original maps with identifications of archaeological items, but these plans have not been available to most researchers, including ourselves. However, the supermap mapping of the archaeological items in Leakey's (1971) monograph permits a detailed analysis of the horizontal dimension of artifacts and bones, which has allowed us to study the orientation of items using Geographic Information System (GIS) technology.

Firstly, site plans were scanned in a raster format (tif format) and georeferenced in a local metric coordinate system using the map scale and the excavation grids (0.14064 < RMS > 0.00415). The resulting raster layers were vectorized and each individual item (bone, artifact or other feature) plotted on Leakey's maps were converted into polygon layers. In this process, standard smoothing algorithms were used to remove small fluctuations in the polygon shapes caused by the grid structure of raster data. The polygon shapes were then linked to an attribute table containing a univocal numeric identification for every element, which includes also metric fields related to the size, shape and strike of every element, as well as descriptive data fields. These descriptive fields included a column for the general classification of every polygon shape (bone, artifact, or natural rock), and more specific fields such as lithic tool type, animal group and anatomical part, as rendered in Leakey's plans.

The metric fields added to the attribute table were length (A-axis), width (B-axis), Elongation Index ($L_l = A$-axis/$B$-axis), and strike of every element. These data were not made available by Leakey in the site plans, but given the precision of her maps, such variables can be accurately calculated using GIS techniques. The
A-axis variable of all stone tools, unmodified rocks and bones was estimated by measuring the length between the antipodal vertices of every polygon (Fig. 1). In some instances, this length does not measure the longitudinal axis of the item (Fig. 1), but it is still an accurate estimator of the longest dimension of items. The B-axis measures the length of a segment perpendicular to the mid part of the A-axis. Both axes were then used to estimate the \( I_e \) (Zingg, 1935). The strike was calculated using the orientation of the A-axis of every item with reference to the Y-axis of the excavation grid (Fig. 1), and then corrected using the north point on Leakey's maps.

Once these variables were calculated with GIS algorithms, we proceeded to analyze the orientation of the items. Since azimuth data are not available, the analysis was based solely on axial data (strike values), comparing the orientation of all elements in each site and then breaking down orientations by general groups (stone tools against fossils). Following previous work (Drake, 1974; Kjaer and Krüger, 1998; Lenoble and Bertran, 2004; Benito-Calvo et al., 2009), our analysis was undertaken on assemblages with \( n > 50 \), which has been proposed as a standard sample (Lenoble and Bertran, 2004). In this analysis, we considered only pieces with Elongation Indices \( I_e > 1.6 \) and length of the A-axis as greater than 2 cm (Bertran and Lenoble, 2002), which reflect more accurately orientation patterns. The method used to estimate the B-axis provided conservative results, yet calculating the B-axis of asymmetric pieces by their mid part does not provide the maximum width. This would necessitate inclusion in the analysis of pieces with an \( I_e < 1.6 \), which does not properly reflect orientation processes.

Angular histograms and statistical tests were used to distinguish uniform (or isotropic) distributions from others, which entail orientation processes (Rao and Sengupta, 1972; Fisher, 1995). Rayleigh's tests compare uniform distributions against unimodal axial distributions, and the omnibus test (Kuiper's test) helps to differentiate isotropic distribution from any non-uniform alternative model (unimodal, bimodal or multimodal). Both tests were used to analyze orientation patterns obtained from Leakey's maps. In the multimodal models, data corresponding to a particular modal group were isolated using the distribution observed in the angular histograms, and then characterized with their vector mean and dispersion parameters, such as the circular standard deviation \( v \), the vector magnitude \( L \), and the concentration \( k \). Circular standard deviation was calculated according to the method proposed by Fisher (1995). \( L \) constitutes the magnitude of the resulting vector expressed as \% (Curray, 1956; Lenoble and Bertran, 2004; Benito-Calvo et al., 2009), and may vary from 0% (the direction of the axis indicates a large dispersion) to 100% (all the measurements in the axis point in the same direction). The \( L \) index can be applied to estimate probability \( p \) according to the Rayleigh test (Curray, 1956). The concentration \( k \) (Fisher, 1995) is a parameter specific to the von Mises distribution (normal distribution in circular data) and measures the beginning of the distribution from a perfect circle (or a uniform distribution, where \( k = 0 \)).

**Results**

The statistical tests and angular histogram results show clear orientation patterns in all of the Bed I sites (DK, FLKNN 3, FLK Zinj, FLK North Levels 6–1). The statistical tests indicate that the Bed I assemblages differ significantly from a uniform model (isotropic or random distribution), which would be expected from archaeological and/or paleontological concentrations undisturbed by natural agents. Kuiper's tests consistently show \( V \) values exceeding the upper 1% point in \( V \) tabulated values (\( V = 2.001, \text{ in Fisher, 1995} \)), which clearly rejects the null hypothesis of uniformity (Table 1). High Rayleigh Z test values and low Rayleigh \( p \) values also suggest sorting processes in all assemblages.

Indeed, angular histograms of all of the sites show polymodal distributions, with a strong trend toward bimodal patterns and

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**Figure 1.** Close-up of the FLK Zinj excavation map as an example of GIS methodology to calculate orientation and measurement of items plotted in Leakey's plans. A) Plan scanning and georeferencing process. B) Vectorization and smoothing of mapped items. C) Geometric procedure to calculate item size (A-axis and B-axis) and orientation (axial direction or strike).
very similar preferred orientation (Fig. 2). The angular histograms indicate a main mode (mmo) and an oblique secondary mode (smo). In several instances, other minor modal groups are patterned perpendicularly to the major modal groups (Fig. 2). The main mode shows orientations following the N–S axis in all of the Bed I sites (Fig. 2, Table 2) apart from FLK North 6, where the orientation is defined by NNW–SSE strikes. On the other hand, the secondary mode indicates SW–NE directions in DK, and NW–SE in the FLK complex. Data from the main and secondary modes are highly clustered, as indicated by the low standard deviation and the high values of the l and k indices (Table 2). The l index is always ≥78%, exceeding 90% in many cases. The k index shows great variance from zero, which represents the minimum concentration. The larger pieces in the main mode range from 32.4 to 100.3 cm of the length of the A-axis (84.3 cm in the FLK North site), and from 22.0 to 54.9 cm in the secondary mode.

In Bed I, only DK, FLK Zinj and FLK North 1–2 yield statistically significant samples to allow comparison of orientation patterns by object type (Fig. 3). The three sites show similar orientation patterns for bones and rocks (natural or artifacts). Bones and stone tools from FLK Zinj and FLK North 1–2 maintain a main N–S direction, while the secondary direction SE–NW is less representative or insignificant in the case of stone tools. In DK, rocks (modified and unmodified stones) and bones have the same general orientation pattern, with a main mode N–S and a secondary mode SW–NE. Nevertheless, in DK the main direction of bones shows two modal groups around the N–S axis.

Discussion

Preferential orientations in some of the Bed I assemblages was first noticed by Potts (1988), although his observations were based on a preliminary visual analysis of the Olduvai excavation maps. Our analysis supports Potts’ observations. The GIS and statistical techniques we have applied indicate a clear strike patterning of bones and stone tools (Figs. 4–6), which is uncharacteristic of in situ assemblages. Our statistical analysis shows a remarkably similar pattern in all assemblages, where two major orientation modes comprise 65.8–85.4% of items (Table 1). Such percentage becomes even higher when perpendicular minor modes are considered. The two major modes follow a main N–S direction and an oblique secondary direction (SW–NE in DK and NW–SE in the FLK complex). Of the FLK complex assemblages, only FLK North 6 displays slight variation in the orientation of objects, which could be linked to the particular characteristics of this assemblage bones and stone tools juxtaposed with large elephant bones (Leakey, 1971).

During transport processes, motion forces and/or collision between particles place items in a position of least resistance to the current. On the other hand, the long axis of items may be positioned transversally to the flow if items have rolled on the depositional surface (Allen, 1984). The two major orientation patterns (mmo and smo) observed in the Bed I assemblages, defined by oblique modes, could be the result of two directions of motion, whereas the minor modes may correspond to items positioned perpendicularly to the motion directions.

Therefore, the orientation patterns obtained in our analysis suggest the action of geological agents on the assemblages, which moved fossils and stone tools in a size range of pieces up to 100.3 cm long (SOM 2). Apart from FLK North 6, the rest of the Bed I assemblages are very similar in average size (9.4–10.5 cm) and have low standard deviation (4.3–5.6), which may suggest that several sites were affected by similar sorting processes. The orientation of pieces is highly clustered (78.4% < L < 95.3%), and orientation patterns are not restricted to particular spots of the sites, but are distributed across the excavation areas exposed by Mary Leakey.

In principle, the sedimentary contexts of Bed I sites do not suggest the existence of high-energy episodes. The Bed I deposits are described mainly as waxy claystones associated with saline lake sediments, tuffs layers and earthy freshwater clays deposited in
lake-margin areas. The Bed I sites are associated with paleosols or exposed surfaces with variable degrees of weathering (Hay, 1973, 1976). The DK assemblages overlie a paleosol developed on an eroded surface affecting tuff and basalts. FLKNN 3 was deposited over a weathered surface of thin claystone above Tuff IB (Hay, 1976), older than that of FLK Zinj (Blumenschine et al., in press). The FLK Zinj paleosol lies on a lacustrine claystone and its archaeological assemblage was buried by Tuff IC (Leakey, 1971; Blumenschine et al., in press). The archaeological levels at FLK North were deposited on exposed surfaces of claystones located below Tuff IF (Leakey, 1971; Hay, 1976; Stollhofen et al., 2008).

The orientation patterns shown in our analysis clearly indicate that the Bed I assemblages were rearranged by post-depositional natural agents. Although in early archaeological sites preferred orientation patterns are usually caused by high-energy events in riverine environments (e.g., Schick, 1984), the generally fine-grained sedimentary contexts of Bed I prevent us from automatically attributing disturbance to fluvial channel processes. Considering possible geological processes that could have operated in the Olduvai Bed I basin, several scenarios can be discussed to ascertain the nature of such disturbance. Mass wasting, sheet erosion, mass flows, fluvial and lakeshore processes, and faulting are possible agents which could potentially have contributed to the movement of archaeological material in the Bed I assemblages, as discussed below.

In clay deposits, variation in humidity may cause post-depositional volume changes of sediments, which can produce mass wasting or creep processes in soils. However, these processes tend to increase the isotropy of the archaeological assemblages being disturbed (Lenoble and Bertran, 2004), which is the opposite trend of the orientation patterns observed in the Bed I assemblages. If creep processes are intense, fabrics may present an organized unimodal linear pattern with the long axis of patterns parallel to

### Table 2
Mean direction and dispersion parameters of the principal modes: mmo, main mode; smo, secondary mode.

<table>
<thead>
<tr>
<th>Bed I sites</th>
<th>Mode</th>
<th>n</th>
<th>μ (°)</th>
<th>L (%)</th>
<th>p</th>
<th>99% confidence interval for μ (°)</th>
<th>k</th>
<th>ψ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DK</td>
<td>mmo</td>
<td>385</td>
<td>175.1</td>
<td>83.6</td>
<td>&lt;1E-12</td>
<td>172.9, 177.4</td>
<td>3.38</td>
<td>17.16</td>
</tr>
<tr>
<td></td>
<td>smo</td>
<td>285</td>
<td>52.0</td>
<td>87.9</td>
<td>&lt;1E-12</td>
<td>049.8, 054.2</td>
<td>4.43</td>
<td>14.56</td>
</tr>
<tr>
<td>FLKNN 3</td>
<td>mmo</td>
<td>199</td>
<td>167.1</td>
<td>95.3</td>
<td>&lt;1E-12</td>
<td>165.3, 168.7</td>
<td>10.81</td>
<td>8.93</td>
</tr>
<tr>
<td></td>
<td>smo</td>
<td>167</td>
<td>118.3</td>
<td>90.0</td>
<td>&lt;1E-12</td>
<td>115.7, 121.0</td>
<td>5.3</td>
<td>13.14</td>
</tr>
<tr>
<td>FLK Zinj</td>
<td>mmo</td>
<td>779</td>
<td>6.6</td>
<td>86.7</td>
<td>&lt;1E-12</td>
<td>005.2, 008.0</td>
<td>4.06</td>
<td>15.33</td>
</tr>
<tr>
<td></td>
<td>smo</td>
<td>410</td>
<td>135.2</td>
<td>91.5</td>
<td>&lt;1E-12</td>
<td>133.7, 136.8</td>
<td>6.19</td>
<td>12.05</td>
</tr>
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<td>FLK North 6</td>
<td>mmo</td>
<td>103</td>
<td>18.0</td>
<td>82.0</td>
<td>&lt;1E-12</td>
<td>013.8, 022.2</td>
<td>3.51</td>
<td>16.74</td>
</tr>
<tr>
<td>FLK North 5</td>
<td>mmo</td>
<td>230</td>
<td>5.6</td>
<td>87.9</td>
<td>&lt;1E-12</td>
<td>003.1, 008.0</td>
<td>4.43</td>
<td>14.56</td>
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<tr>
<td></td>
<td>smo</td>
<td>120</td>
<td>124.8</td>
<td>88.0</td>
<td>&lt;1E-12</td>
<td>121.4, 128.1</td>
<td>4.48</td>
<td>14.47</td>
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<td>FLK North 4</td>
<td>mmo</td>
<td>143</td>
<td>179.2</td>
<td>81.3</td>
<td>&lt;1E-12</td>
<td>175.3, 183.1</td>
<td>3.03</td>
<td>18.45</td>
</tr>
<tr>
<td></td>
<td>smo</td>
<td>47</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>FLK North 3</td>
<td>mmo</td>
<td>264</td>
<td>7.2</td>
<td>85.1</td>
<td>&lt;1E-12</td>
<td>004.7, 009.8</td>
<td>3.68</td>
<td>16.26</td>
</tr>
<tr>
<td></td>
<td>smo</td>
<td>122</td>
<td>163.4</td>
<td>91.7</td>
<td>&lt;1E-12</td>
<td>160.6, 166.2</td>
<td>6.33</td>
<td>11.91</td>
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<tr>
<td>FLK North 1–2</td>
<td>mmo</td>
<td>948</td>
<td>9.4</td>
<td>78.4</td>
<td>&lt;1E-12</td>
<td>007.8, 011.1</td>
<td>2.68</td>
<td>19.99</td>
</tr>
<tr>
<td></td>
<td>smo</td>
<td>623</td>
<td>126.2</td>
<td>83.0</td>
<td>&lt;1E-12</td>
<td>124.4, 128.0</td>
<td>3.27</td>
<td>17.52</td>
</tr>
</tbody>
</table>

**Figure 3.** Angular histograms comparing orientation of bones and rocks (unmodified and artifacts) at DK, FLK North 1–2 and FLK Zinj.
Although some < 1 m reliefs are detected in the FLK area (Blumenschine et al., in press), the palaeotopography of the Olduvai Bed I basin usually shows very low gradients described as flat terrains (Hay, 1973, 1976; Blumenschine et al., in press), which differs notably from the minimum slopes (9–42°) required to produce linear fabrics caused by creep processes (Mills, 1983).

On the other hand, if the clays were saturated in water, solution or downslope flow of sediments could occur, causing strongly linear fabrics (Bertran et al., 1997, 2010). However, solution or intense creep processes are more characteristic of periglacial systems, which differ notably from the semiarid Olduvai Bed I basin. Besides, unimodal orientation patterns related to intense creep or solution processes (Mills, 1983; Bertran et al., 1997, 2010) do not explain the oblique bimodal distribution observed in the Bed I assemblages. Another factor to consider is that these geological processes, which are likely to leave clear signatures in deposits, are not reported in Olduvai Bed I (Hay, 1976; Stollhofen et al., 2008). Thus far, only paleosols, root marks, and diagenetic and pedogenetic neoformation of clays have been identified as post-depositional disturbance agents (Hay, 1976; Hay and Kyser, 2001; Hover and Ashley, 2003), but such processes do not cause the kind of orientation patterning observed in the Bed I archaeological assemblages (Fig. 2, SOM 1, 2B and 2C).

Depositional processes in the Olduvai basin are mainly related to fluvial, volcanoclastic, aeolian, and lake-margin systems, which have been affected by faulting processes. Fluvial processes are dominant to the east in the alluvial fan area, but also occur closer to the Bed I sites excavated by Leakey (Hay, 1976; Stollhofen et al., 2008; Blumenschine et al., in press). These fluvial agents are known to have reworked tuffs and incised narrow and steep-sided channels, such as those described in the DK and FLK Zinj paleosols (Hay, 1976; Blumenschine et al., in press). However, objects with preferred orientation in the Leakey sites do not seem to be associated with linear structures (i.e., channels, SOM 1) and the orientation pattern observed (oblique bimodal) is not characteristic of traction flows. As pointed out by several authors, fluvial environments are characterized by traction current flows driven by the slope, which at any one locality, such as an archaeological site, tend to be unimodal (Selley, 1968; Potter and Pettijohn, 1977; Allen, 1984; Prothero and Schwab, 2004). Consequently, the orientation of items to the current tends to be parallel or perpendicular, but not oblique.

Sheet erosion, such as rainwash or run-off processes, could also produce reworking of assemblages. When these processes operate, the A-axis of items tends to orientate parallel to the local slope, although some items are positioned perpendicular to the slope, producing similar patterns to those of fluvial processes (Bertran et al., 1997). This would produce mainly unimodal distributions or orthogonal bimodal patterns with items orientated perpendicular or parallel downslope. In run-off processes, preferred orientation patterns occur in steep slopes (Bertran et al., 1997). Therefore, for run-off processes to be the cause of the orientation patterns described in this study, a significant N–S paleoslope would have to exist in all of the Bed I assemblages, which show strikes dominated by an N–S main mode. Although the FLK Zinj site is now known to be
Figure 5. Map of FLK Zinj showing the major preferred orientations (see also SOM 1).
located on a topohigh (Blumenschine et al., in press), it is unclear how slope run-off processes would affect the Zinj assemblage (located on top of such a low gradient relief) and the rest of nearby (FLKN and FLKNN) and more distant (i.e., DK) sites. Equally, if an N–S paleoslope was documented in all of the Bed I sites, mass wasting features would probably be detected in the deposits as well. Recently, Stollhofen et al. (2008) have reported sheet wash and sheet flood processes in the Bed I deposits, but the effect of these agents over the specific sites studied here remains unknown. Besides, rainwash and run-off processes do not provide a satisfactory explanation for the oblique secondary mode, which is present in all assemblages and is especially conspicuous in FLKN 3 (Fig. 4), FLK Zinj (Fig. 5), and DK (Figs. 2 and 3).

Another possible scenario to explain the oblique mode by slope-driven processes would be to consider the role of faulting. Displacement of deposits by faulting during the downslope rearrangement of assemblages could change the slope direction. Then, fluviatile, gravitational or sheet erosion processes could re-orientate some of the items in a new direction. Faulting has been reported to affect some of the sites, such as FLK North (Leakey, 1971), and Stollhofen and Stanistreet (in press) document river deflection by NNW–SSE running fault scarps in Beds I and Lower Bed II. Although topographic relief generated by faulting would have an important effect on the direction of rivers, pyroclastic flows and other transport agents, it is unlikely that faulting activities influenced all of the assemblages in the same manner as to systematically produce the same bimodal orientation. On the other hand, rainwash and/or run-off processes do not satisfactorily explain the abundance of very small items in some of the Bed I assemblages. If these processes were capable of orienting pieces with an A-axis of 50 cm length (SOM 2), items less than 2 cm, which are very abundant in sites such as FLK Zinj, would be washed off during downslope erosion. Volcanic mass flows (i.e., surges) are also known to produce parallel-to-flow orientation of natural clasts (Karátson et al., 2002), so there is no reason why they could not have the same effect in archaeological assemblages. Several of the Bed I assemblages are associated to tuff deposits. For example, FLK Zinj was covered by Tuff IC (Leakey, 1971; Hay, 1976; Blumenschine et al., in press) and FLKN 1–2 was covered by Tuff IF (Leakey, 1971). Although transport processes are documented for these tuffs (e.g., Stollhofen et al., 2008), Tuff IC and IF are primarily subaerial deposits (Hay, 1976; McHenry et al., 2008; Stollhofen et al., 2008). Furthermore, these tuffs do not affect all of the archaeological sites, so volcaniclastic mass flows do not fully explain the bimodal distribution of remains in most of the assemblages.

Other processes that generate multimodal and bimodal distributions are related to aeolian and shoreline environments (Selley, 1968; Potter and Pettijohn, 1977; Allen, 1984; Prothero and Schwab, 2004). Aeolian processes affecting tuffs in Olduvai have been reported (Hay, 1976; Stollhofen et al., 2008) and could be responsible for the deflation of the smallest bone and lithic particles, absent in several assemblages (e.g., FLKN levels 6–3, FLKNN levels 3–2 and DK). However, aeolian processes are unlikely to be responsible for the orientation patterns of the fossils and stone tools plotted on Leakey’s maps, given the considerable size of most of them (SOM 2).

Lake shorelines can have complex circulations controlled mainly by waves and surface currents driven by wind direction (Bridge and Dемичко, 2008). Prevalent winds in the Olduvai basin were described as easterly (Hay and Kyser, 2001), which would cause waves with N–S crests. Nagle (1967) documented that fossils affected by shore currents tend to align parallel to waves, so this pattern would explain the consistent main N–S direction of items in all of the Bed I assemblages. Stollhofen et al. (2008) also report the predominance of northeasterly winds toward 215–255°. This would be consistent with waves following the NW–SE axial direction of the secondary mode at the FLK North assemblages (NW–SE, Table 2). In fact, Stollhofen et al. (2008) have identified wave ripple crests with a NW direction (312°). Regarding the secondary mode NE–SW from DK, no indicators of parallel waves have been described so far, but the NE paleo-wind directions affecting Tuff IF (Stollhofen et al., 2008) or the NE–SW lake shoreline described by Hay (1973, 1976) match with the secondary axial direction at DK (Table 2). Although wind directions provide a reasonable explanation to understand orientation modes of the Bed I assemblages and wave
rereworking of muds and oolitic sands has been reported in the Olduvai Bed I basin (Hay, 1973: p. 547, 1976: p. 43), the lake shoreline hypothesis presents also several problems. Paleogeographic reconstructions indicate that the Olduvai lake shoreline had withdrawn during the formation of the Bed I sites (Hay, 1976; Stollhofen et al., 2008; Blumenschine et al., in press). Therefore, lake transgressions and/or regressions were unlikely to contribute to the rearrangement of some assemblages, such as FLK Zinj or FLKN 1–2, which in fact were buried by subaerial deposits. During the formation of the Bed I sites, the area was dominated by semiarid freshwater wetlands with abundant marshes, swamps and pools (Hay, 1973, 1976; Liutkus and Ashley, 2003; Blumenschine et al., in press). New reconstructions (Blumenschine et al., in press) place FLKNN within the wetland interior, and FLKN and FLK Zinj are only a few hundred meters to the south. Kinematic processes described above for lakes can also be applied to marshes, swamps and pools, for the effect of waves in wetland water bodies is also well attested (i.e., Schwimmer and Pizzuto, 2000). Therefore, it may be proposed that wave movement in wetland water bodies could have had a significant impact on the formation of assemblages. In fact, aligned woody plant stems and/or branches have been reported in the wetland shore of the FLK area, transported by water or gravity processes (Blumenschine et al., in press). These closed pools follow the directions of 40–220° and 26–206° (Blumenschine et al., in press), which are in the dispersion range of the N–S main orientation described for the Bed I assemblages (Fig. 1), and coincide with the direction of easterly winds.

The hypothesis of wave disturbance by freshwater bodies works reasonably well for FLKNN, and to a minor extent, for FLKN, DK and FLK Zinj. Sedimentological, faunal and macroplant data indicate that FLKNN was well inside a wetland environment (Blumenschine et al., in press) and these settings are known to be flooded periodically. The FLKNN faunal assemblages excavated by Leakey show a deficit of small fragments (Domínguez-Rodrigo et al., 2007) and the same applies to lithics, among which debris are nearly absent (de la Torre, pers. obs.). Interestingly, new excavations in the FLKNN area also yielded very few small sized remains (Blumenschine et al., in press). Therefore, it could be proposed that the FLKNN area was periodically flooded, and water removed smaller items and orientated the larger ones. Although the ecological context of DK is not as well known as the FLK area, the presence of channels (Potts, 1988) and the role of water disturbance over the lithics has long been recognized (e.g., de la Torre and Mora, 2005a). However, until further studies become available, there are very few arguments that can be used to support or dismiss the hypothesis of wave rearrangement of the DK material. FLKNN was located in a similar ecological setting as FLKNN, so it would be reasonable to expect that some of the levels were periodically flooded by freshwater. de la Torre and Mora (2005a) reported the acute shortage of the small fraction of debris in FLKNN levels 6–3, which now can be explained by winnowing caused by marshland flooding.

New reconstructions of the paleotopographical and paleoecological setting of FLK Zinj (Blumenschine et al., in press) locates this site on a topohigh adjacent to the wetlands. Wave action over the assemblages could have occurred during flooding events, in which areas raised above the wetlands, like FLK Zinj, could also have been inundated. Blumenschine et al. (in press) report flooding of the raised area due to the action of streams, and water was probably retained by the proximity of the wetlands and the levee structures described in the river channels. In this context, wave action could also have reworked materials at the sites located in raised areas like FLK Zinj. However, the abundance of very small items in FLK Zinj represents inconsistencies on the wetland wave disturbance scenario. A possibility to explain the high number of small fragments would be that rearrangement of items was caused by the action of a closed water body, such as a local pond. Given the unevenness of the FLK Zinj paleosurface (Blumenschine et al., in press), it could hypothetically be proposed that irregularities on the surface formed depressions that were flooded by the processes described above. These closed pools could have preferentially orientated archaeological items through wave action caused by prevailing winds, but would have not winnowed the assemblages. Of course, this is only a working hypothesis that must be tested with more detailed paleotopographical data. Leakey (1971) reported a small channel and an oblong hollow in the FLK Zinj excavation area, but for this scenario to be confirmed, clearer indicators of topographic depressions must be found.

Whatever scenario is proposed, the strong orientation patterns of the bones and artifacts suggest that the view of the Bed I sites as broadly in situ assemblages should be seriously reconsidered. The Bed I assemblages show clear orientation distribution with a high degree of clustering that includes a wide range of object sizes. It should be admitted, however, that none of the geological processes described so far in the Olduvai Bed I basin alone explains the orientation patterns reported in this paper. On the other hand, it must be remembered that the lack of high-energy sedimentological markers does not automatically preclude the possibility that they operated at the sites. Most of the Bed I assemblages lay on paleosols and weathered land surfaces (Hay, 1976). By definition, paleosols involve periods of non-deposition and during these hiatuses, for which no sedimentary record is preserved, a variety of orientation agents could have affected the assemblages.

Geological agents characterized by unidirectional flows (fluvial, rainwash, gravitational or volcanoclastic) do not alone explain the oblique bimodal orientation pattern described here. This would require us to consider subsequent changes in the direction of flows, for example in the direction of local slopes due to faulting. Although this could have happened, this is a rather convoluted explanation that would have required the action of different geological agents operating in the same manner in different sites and periods. The effect of the Olduvai paleo-lake shoreline should be ruled out for the moment, due to the absence of lake flooding indicators over the assemblages. On the other hand, wave action in wetlands areas, characterized by multimodal flows driven by the prevailing wind, provides a reasonable explanation of the orientation patterns here described, although more sedimentary and paleotopographical data on the local contexts is needed before this and alternative hypotheses can be compared.

Conclusions

The assemblages excavated by Mary Leakey (1971) in Olduvai Bed I have been key to all recent interpretations of early human behavior (Isaac, 1978; Binford, 1981; Potts, 1984; Rose and Marshall, 1996). Despite the frequently opposing interpretations of the very same record concerning the role of carnivores and humans in the formation of the assemblages, researchers have tended to agree that, whatever the involvement of these biological agents was, most of the Bed I sites represent biostratigraphic accumulations with little or no role for post-depositional agents (e.g., Potts, 1988; Capaldo, 1997; Domínguez-Rodrigo et al., 2007). This presumption is usually based on the low energy sediments (clays and silts) where the Bed I sites are deposited (Leakey, 1971; Hay, 1976), which have been considered sufficient to assume that the assemblages were in primary position.

However, in this paper we have argued that disturbance could have played a more important role in the shaping of the Bed I assemblages than previously thought. Our application of GIS techniques to the site plans and analysis of the strike of items indicate strong preferential orientations affecting most of the artifacts and
bones. Moreover, the assemblages from the FLK complex (FLK Zinj, FLKN 5, 4, 3 and 1–2, and FLKNN 3) present the same orientation patterns, which are also consistent in DK and FLKN 6. The orientation patterns are characterized by two oblique modes, suggesting two directions of flow (N–S in all the sites, plus SW–NE in DK and NW–SE in the FLK complex). The modes are highly clustered, comprised mostly of lithics and bones. Orientated items are not restricted to particular spots in the sites, but are distributed uniformly across the excavation areas exposed by Mary Leakey.

The sedimentary record of Bed I in the Olduvai basin shows several processes, which could have oriented the archaeological and paleontological remains. Faulting, sheet erosion, mass wasting, mass flows, fluvial, and lakeshore and wetland flooding, are possible processes that could have contributed to the rearrangement of items. We have discussed a range of possibilities based on the available data, but none of these geological processes provides a definitive explanation to match what we know about the local sedimentary contexts with the orientation patterns described in this paper. Data on the local sedimentary contexts is still limited, which makes the site-by-site discussion of the formation agents difficult.

Therefore, it is clear that more detailed sedimentological, paleo-geographic and paleotopographical reconstructions are required to fully understand the formation dynamics of the assemblages. New research shall include detailed stratigraphic information of the archaeological levels and the strata below and above, as well as an investigation of the synedepositional tectonic structure of each site. All of this should be contextualized within the sedimentary, erosive and tectonic processes operating in the Olduvai basin, and linked with fresh archaeological data of orientation patterns and size classes of fossils and stone tools at the Olduvai Bed I assemblages.

While acknowledging that new, high-resolution geological and archaeological research is required to provide satisfactory explanations of the formation processes, the aim of this paper is to demonstrate that abiotic agents played a much more important role at Bed I than previously believed. Leakey’s maps indicate that there are preferential orientation patterns in the Olduvai Bed I assemblages, and therefore it is questionable whether they are in pristine condition. This has important implications for the behavioral models based on the Olduvai Bed I record. Application of GIS techniques, still uncommon in paleoanthropology, demonstrates that the formation history of Bed I sites was a very complex one indeed.

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Appendix. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhevol.2011.02.011.

References


